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Regular Publications

The Society issues annually a single serial octavo publication entitled Bulletin of the Geological Society of America. The first twenty volumes of this serial consist of *proceedings* and *memoir brochures*, the former containing the records of meetings, with abstracts and short papers, list of Fellows, etcetera, and the latter embracing larger papers accepted for publication. Beginning with this volume (21), the Bulletin will be issued in four parts per year (volume), at intervals of three months each. A small supply of authors' separates of the longer articles will be kept for sale by the Secretary.

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* Copies of the "Constitution and By-Laws and Publication Rules" printed as part of the "Proceedings" may be had separately at the cost of 10 cents to members and 15 cents to the public. Copies also of the "List of Officers, Correspondents, and Fellows" may be had by members for 15 cents and by the public for 25 cents; the remainder, containing reports of officers and committees, memoirs, etcetera, may be had by members for 45 cents and by the public for 65 cents.

Brochures.	Pages.	Plates.	Figures.	Price to Fellows.	Price to the Public.
Geologic work of ants in tropical America. J. C. Branner........	449–496	35	1–11	.50	.75
Internal characters of some Mississipian Rhynchonelliform shells. S. Weller..	497–516	....	1–18	.20	.30
New light on the geology of the Wasatch Mountains, Utah. E. Blackwelder	517–542	36–40	1–9	.40	.60
Relations of present profiles and geologic structures in desert ranges. C. R. Keyes....................	543–564	....	1–16	.20	.30
Deflation and the relative efficiencies of erosional processes under conditions of aridity. C. R. Keyes.	565–598	....	1–6	.35	.50
Beach cusps. D. W. Johnson.....	599–624	41–42	1–6	.30	.45
Criteria for the recognition of the various types of sand grains. W. H. Sherzer.................	625–662	43–47	....	.55	.80
Rock streams of Veta Peak, Colorado. H. B. Patton............	663–676	48–52	....	.30	.45
Ordovicic-Siluric section of the Mingan and Anticosti islands, Gulf of Saint Lawrence. C. Schuchert and W. H. Twenhofel..........	677–716	....	....	.40	.60
Some effects of glacial action in Iceland. F. E. Wright............	717–730	....	1–2	.15	.20
Tables for the determination of crystal classes. W. S. T. Smith......	731–736	....	....	.10	.15
Additional note on the geometry of faults. H. F. Reid...............	737–740	....	1–2	.10	.15
Supplementary note on the organization of the Geological Society of America. C. H. Hitchcock.....	741–746	....	....	.10	.15
Richmond and Great Barrington bowlder trains. F. B. Taylor...	747–752	....	1	.10	.15
Abstracts of papers presented at the Twenty-second Annual Meeting of the Society, but not published in full in the preceding pages of this volume, together with discussions of papers as far as preserved. E. O. Hovey, *Secretary*..........	753-788	53–54	....	.40	.60
Proceedings of the Eleventh Annual Meeting of the Cordilleran Section of the Geological Society of America, held at Berkeley, California, March 25 and 26, 1910. G. D. Louderback, *Secretary*...........	789–796	....	....	.10	.15

Irregular Publications

In the interest of exact bibliography, the Society takes cognizance of all publications issued wholly or in part under its auspices. Each author of a memoir receives 30 copies without cost, and is permitted to order any additional number at a slight advance on cost of paper and presswork; and these separate brochures are identical with those of the editions issued and distributed by the Society. Contributors to the proceedings are also authorized to order any number of separate copies of their papers at a slight advance on cost of paper and presswork; but such separates are bibliographically distinct from the brochures issued by the Society.

The following separates of parts of volume 21 have been issued:

Editions uniform with the Brochures of the Society

Pages	87–118,		310 copies.	March	31,	1910.
"	119–140,	plate 2;	180 "	"	31,	1910.
"	141–178,	" 3;	530 "	May	26,	1910.
"	179–226,	" 4;	200 "	June	3,	1910.
"	227–248,	" 5;	50 "	"	10,	1910.
"	249–284,	plates 6–17;	80 "	"	15,	1910.
"	285–294,		50 "	"	25,	1910.
"	295–312,		50 "	"	25,	1910.
"	313–338,	" 18–28;	180 "	July	2,	1910.
"	339–406,	" 29–30;	230 "	"	5,	1910.
"	407–432,	plate 31;	30 "	"	20,	1910.
"	433–440,		130 "	August	10,	1910.
"	441–446,		130 "	"	10,	1910.
"	447–448,	plates 32–34;	130 "	"	10,	1910.
"	449–496,	plate 35;	200 "	"	20,	1910.
"	497–516,		130 "	September	10,	1910.
"	517–542,	plates 36–40;	80 "	"	24,	1910.
"	543–564,		30 "	October	12,	1910.
"	565–598,		30 "	"	13,	1910.
"	599–624,	" 41–42;	180 "	November	24,	1910.
"	625–662,	" 43–47;	30 "	"	15,	1910.
"	663–676,	" 48–52;	110 "	December	15,	1910.
"	677*–716,		360 "	"	23,	1910.
"	717–730,		330 "	"	24,	1910.
"	731–736,		50 "	"	31,	1910.
"	737–740,		80 "	"	31,	1910.
"	741–746,		55 "	"	31,	1910.
"	747–752,		100 "	"	31,	1910.

Special Editions†

Pages	5–12‡,	plate 1;	30 copies.	March	31,	1910.
"	12–16,		30 "	"	31,	1910.
"	17–19,		230 "	"	31,	1910.
"	42–52,		130 "	"	31,	1910.
"	53–68,		30 "	"	31,	1910.
"	69–86,		230 "	"	31,	1910.
"	771–773,	plates 53–54;	200 "	December	31,	1910.

* Under the brochure heading is printed PROCEEDINGS OF THE PALEONTOLOGICAL SOCIETY.

† Bearing imprint [From Bull. Geol. Soc. Am., vol. 21, 1909].

‡ Fractional pages are sometimes included.

CORRECTIONS AND INSERTIONS

All contributors to volume 21 have been invited to send corrections and insertions to be made in their papers, and the volume has been scanned with some care by the Editor. The following are such corrections and insertions as are deemed worthy of attention :

Plate 4, opposite page 217 ; *for* "Bathymetrical chart of the oceans" *read* Bathymetrical chart of the Atlantic Ocean

Page 282, line 18 from top ; *for* "femur" *read* humerus

" 284, after "plate 15" *should read* figures 1, 2, 5, right humeri ; all others left humeri

Page 284, line 14 from top; *for* "proximal" *read* distal

" 287, line 24 from top; *for* "Sp. augusta" *read* Sp. angusta

" 296, line 5 from top; *omit* "(2*a*)"

" 316, line 4 from bottom ; *omit* "Scale, 1:400,000"

" 322, *reverse* figure 1 of plate 20

" 328, footnote; *for* "E. O. Hovey" *read* H. C. Hovey

" 341, line 8 from bottom; *for* "figure 6" *read* figure 7

" 342, line 1 ; *for* "figure 6" *read* figure 8

" 343, last line ; *for* "parellel" *read* parallel

" 344, line 11 from top; *for* "figure 3" *read* figure 5

" 344, line 4 from bottom; *for* "figure 3" *read* figure 5

" 345, line 11 from bottom; *for* "Gwillem" *read* Gwillim

" 348, line 8 from bottom; *for* "730" *read* 670

" 358, line 12 from top; *for* "H. B. Ritter" *read* H. P. Ritter

" 361, line 18 from top ; *for* "F" *read* G

" 380–2, under amplitude in tables; *for* "inches" *read* ″ (meaning seconds.)

" 395, lines 5–6; *for* "the symbol *" *read* a black star

" 398, footnote 117; *for* "Aljjaska" *read* Aljaska, and *for* "No" *read* N. O.

" 401, line 7 from top; *for* "figure 8" *read* figure 4

" 406, line 17 from bottom ; *for* "excepted" *read* except

" 528, line 9 from bottom; *omit* "Upper"

" 768, line 16 from bottom; *for* "Kaluea" *read* Kilauea

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 21, PP. 1-68, PL. 1 MARCH 31, 1910

PROCEEDINGS OF THE TWENTY-SECOND ANNUAL MEETING OF THE GEOLOGICAL SOCIETY OF AMERICA, HELD AT BOSTON AND CAMBRIDGE, MASSACHUSETTS, DECEMBER 28, 29, 30, AND 31, 1909[1]

EDMUND OTIS HOVEY, *Secretary*

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[1] The business sessions of the twenty-second annual meeting of the Society were held in the rooms of the departments of Geology, Mineralogy, and Botany of the University Museum, Harvard University. The meetings in general were presided over by First Vice-President F. D. Adams in the absence of President G. K. Gilbert, who was detained by ill health in Washington, D. C.

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Session of Tuesday, December 28

The first session of the Society was called to order at 10 o'clock a. m., Tuesday, December 28, in the lecture hall of the Department of Geology, University Museum, Cambridge, Mass., by Vice-President Adams, who, after a few fitting words with reference to the absent President, announced that the submission of the Council Report would necessarily be deferred, since it had not yet been received from the printers.

ELECTION OF AUDITING COMMITTEE

Nominations for the Auditing Committee to examine and report upon the Treasurer's books and vouchers and the securities in his custody were then called for. F. L. Ransome, H. Ries, and S. F. Emmons were nominated and duly elected as this committee.

ELECTION OF OFFICERS, FELLOWS, AND CORRESPONDENTS

The declaration of the votes for officers for 1910, for Fellows, and for Correspondents being next in order, the Secretary announced the election in due form of the regular tickets, as follows:

OFFICERS FOR 1910

President:

Arnold Hague, Washington, D. C.

First Vice-President:

Charles Schuchert, New Haven, Conn.

Second Vice-President:

A. P. Low, Ottawa, Ont.

Secretary:

Edmund Otis Hovey, New York City.

Treasurer:

William Bullock Clark, Baltimore, Md.

Editor:

Joseph Stanley-Brown, Cold Spring Harbor, N. Y.

Librarian:

H. P. Cushing, Cleveland, Ohio.

Councilors:

J. B. Woodworth, Cambridge, Mass.
C. S. Prosser, Columbus, Ohio.

FELLOWS

William Clinton Alden, A. B. (Cornell College); A. M., Ph. D. (Chicago), Washington, D. C. Assistant Geologist, U. S. Geological Survey.

Wallace Walter Atwood, B. S., Ph. D. (Chicago, '97, '03), Chicago, Illinois.

Edson Sunderland Bastin, A. B. (Michigan, '02); A. M. (Chicago, '03), Washington, D. C. Assistant Geologist, U. S. Geological Survey.

Edward Wilber Berry, Baltimore, Md. Instructor in Johns Hopkins University.

Willis Stanley Blatchley, A. B., A. M. (Indiana, '87, '91), State House, Indianapolis, Indiana. State Geologist of Indiana.

Henry Andrew Buehler, B. S. (Wisconsin, '01), Rolla, Missouri. State Geologist of Missouri.

Fred Harvey Hall Calhoun, B. S., Ph. D. (Chicago, '93, '02), Clemson College, South Carolina. Professor of Geology and Mineralogy, Clemson College, and Assistant Geologist, U. S. Geological Survey.

Arthur Louis Day, B. A., Ph. D. (Yale, '92, '94), Washington, D. C. Director, Geophysical Laboratory, Carnegie Institution of Washington.

Frank Walbridge De Wolf, S. B. (Chicago, '03), Urbana, Illinois. Assistant State Geologist of Illinois and Assistant Geologist, U. S. Geological Survey.

James Walter Goldthwait, A. B., A. M., Ph. D. (Harvard, '02, '03, '06), Hanover, New Hampshire. Assistant Professor of Geology in Dartmouth College and head of department.

Baird Halberstadt, Pottsville, Pennsylvania. Engineer and Geologist.

Oscar H. Hershey, Kellogg, Idaho. Engaged in private practice.

Frederick Brewster Loomis, B. A. (Amherst); Ph. D. (Munich), Amherst, Massachusetts. Professor of Comparative Anatomy in Amherst College.

Richard Swann Lull, B. S., M. S. (Rutgers, '93, '96); Ph. D. (Columbia, '03), New Haven, Connecticut. Assistant Professor of and Associate Curator in Vertebrate Paleontology, Yale University.

George Rogers Mansfield, B. S., A. M. (Amherst, '97, '01); A. M., Ph. D. (Harvard, '04, '06), Evanston, Illinois. Assistant Professor of Geology, Northwestern University.

Lawrence Martin, A. B. (Cornell, '04); A. M. (Harvard, '06), Madison, Wisconsin. Instructor in Geology, University of Wisconsin, and Geologic Aid, U. S. Geological Survey.

Samuel Washington McCallie, Ph. B. (Tennessee Wesleyan), Atlanta, Georgia. State Geologist of Georgia.

William John Miller, S. B. (Pacific, '00); Ph. D. (Johns Hopkins, '05), Clinton, New York. Professor of Geology and Mineralogy in Hamilton College.

Malcolm John Munn, Washington, D. C. Assistant Geologist, U. S. Geological Survey.

Edward Orton, Jr., E. M. (Ohio State University, '84), Columbus, Ohio. Director, Department of Ceramic Engineering, Ohio State University, and Assistant Geologist, Geological Survey of Ohio.

Philip S. Smith, A. B., A. M., Ph. D. (Harvard, '99, '00, '04), Washington, D. C. Assistant Geologist, U. S. Geological Survey.

Warren Du Pré Smith, B. S. (Wisconsin, '02); A. M. (Leland Stanford, Jr., '04); Ph. D. (Wisconsin, '08), Manila, Philippine Islands. Chief of the Mining Bureau.

Cyrus Fisher Tolman, Jr., B. S. (Chicago, '96), Tucson, Arizona. Professor of Geology and Mining in the University of Arizona.

Charles Will Wright, B. S. and M. E. (Michigan College of Mines, '03), Washington, D. C. Assistant Geologist, U. S. Geological Survey.

CORRESPONDENTS

Charles Barrois, Professor of Geology at the University, Lille, France.

W. C. Brögger, Professor of Geology and Mineralogy at the Royal University, Christiania, Norway.

Sir Archibald Geikie, President of the Royal Society, late Director General of the Geological Survey of the United Kingdom, Hasslemere, England.

Albrecht Heim, President of the Swiss Geological Commission, Professor of Geology at the University, Zürich, Switzerland.

Emanuel Kayser, Professor of Geology at the University, Marburg, Germany.

Eduard Suess, Professor (retired) of Geology at the Imperial-Royal University, President of the Academy of Sciences, Vienna, Austria.

Ferdinand Zirkel, Professor (retired) of Mineralogy and Geology at the University of Leipzic, Bonn, Germany.

The Secretary announced the death during the past year of Persifor Frazer and Daniel W. Langton. The memorials of these members, read by title, were as follows:

PERSIFOR FRAZER

MEMOIR OF PERSIFOR FRAZER

BY R. A. F. PENROSE, JR.

Dr. Persifor Frazer was born in Philadelphia, July 24, 1844, and died in the same city April 7, 1909. He was the son of John Fries Frazer and Charlotte Cave Frazer. His family were among the early settlers of Pennsylvania in the colonial days, having come originally from Scotland, and the town of Frazer, in eastern Pennsylvania, was named for the Frazer family in America. The Frazers have always been prominent in the affairs of the State and nation. Gen. Persifor Frazer, the son of the first of the family in America, was the great-grandfather of Dr. Persifor Frazer, and commanded with distinction in the Revolutionary War. Robert Frazer, the grandfather of Dr. Persifor Frazer, was an eminent lawyer in Philadelphia and a member of the Pennsylvania legislature.

John F. Frazer, LL. D., the father of Persifor Frazer, was professor of chemistry for many years at the University of Pennsylvania, and also vice-provost of the same institution. He was one of the most eminent scientific men of his time in America, and there still live men who can recall with pleasing remembrance the informal Sunday evening gatherings at Professor Frazer's house in Philadelphia, where the scientific questions of the day were discussed. In these weekly assemblages were to be found such men as Dr. John L. Le Conte, Professors Genth and Lesley, and other local scientists, as well as scientists from elsewhere, who happened by chance to be in Philadelphia. His hospitality to his fellow-workers became known far beyond the limits of the city, and many a man of science found a congenial haven at his house.

Persifor Frazer was brought up among these surroundings, and his natural inclination for science had every opportunity to develop in such an atmosphere. One of the earliest traits that manifested itself in him was his remarkable versatility, and nothing in any branch of science or human affairs failed to interest him. This trait was rapidly developed in his youth by intercourse with the masters of various branches of science who assembled at his father's house; and no better evidence of his versatility is shown than the fact that in later life he acquired eminence in three distinct branches of learning—chemistry, geology, and the study of handwriting. He was also an accomplished linguist, speaking French and German as he would English, and with this he combined remarkable powers as a conversationalist and speaker. As a public lecturer he always commanded the respect and attention of his audience by his eloquent and lucid address. In another direction his versatility was shown when he served with marked credit and distinction in both the Army and the Navy during the Civil War. He was also devoted to athletics and was noted for his prowess in fencing and sparring.

Persifor Frazer's early training was in Saint Lukes Parish School, and later in the schools of Samuel Arthur and of Rev. John W. Faires, all in Philadelphia. In 1858 he entered the University of Pennsylvania, from which he graduated with the degree of A. B. in 1862. He received the degree of A. M. from the same institution in 1865. Immediately after leaving college in 1862 he joined the United States Coast Survey, and was connected with the South Atlantic squadron in 1862 to 1863. The Civil War was then at its height, and Frazer returned North, enlisted with the First Troop, Philadelphia City Cavalry, and fought through the Gettysburg campaign in 1863. Later he joined the United States Navy as acting ensign, and served in the Mississippi squadron until the end of the war, when he received an honorable discharge and an expression from the Navy Department of its high appreciation of his services.

After the close of the war, Frazer studied chemistry for a few months with the firm of Messrs. Booth and Garrett, in Philadelphia. In 1866 he went to Germany to continue his scientific studies, and attended the Royal Saxon School of Mines at Freiberg from 1866 to 1869. On his return to America in the latter year he became mineralogist and metallurgist to the United States Geological Survey under Hayden, in which position he carried on explorations in Colorado and New Mexico and wrote reports on the results of his work. He remained on the U. S. Geological Survey until 1870, when he was appointed instructor in "natural philosophy and chemistry" at the University of Pennsylvania, a department in which his father was then head professor. In 1871 he was elected assistant professor in the same department, and on the death of his father, in 1872, he succeeded him as head of the department. In 1873 the chair of natural philosophy and chemistry was divided into two professorships, one of chemistry and one of physics, and Frazer was appointed professor of chemistry.

Though a most efficient and able chemist, Frazer's inclinations seem to have been more strongly in the direction of geology. His education in this subject at Freiberg and on the U. S. Geological Survey under Hayden led him to seek for the reëstablishment of a geological survey in Pennsylvania. The previous geological survey of Pennsylvania had long since been discontinued for lack of an appropriation from the legislature, but as the result of the persistent efforts of a number of scientific men in Pennsylvania, among whom was Frazer, the legislature, in 1874, made an appropriation for a new geological survey of the State. Prof. J. P. Lesley was appointed head of the survey, and Frazer resigned his professorship of chemistry to take charge of the geological work in some of the counties in the southeastern part of the State. The geology in this region is in many cases very complicated, and the highest scientific ability was required in solving the many problems involved. Frazer, however, showed himself thoroughly capable of handling the task, and in a masterly way he worked out the structure and other intricate geological problems of the region in great detail. This work brought him more into the public eye and gave him more prominence than anything he had previously done. Four volumes of the publications of the Second Geological Survey of Pennsylvania and a monograph in another volume attest to the energy with which he pursued his geological researches during the eight years in which he was connected with that organization.

In 1881 Frazer was general manager of the Central Virginia Iron Company. Somewhat later he took up the practice of his profession as consulting and reporting geologist, chemist, metallurgist, and mining engineer, and continued in it for many years. This led him to many different parts of the United States and foreign countries, and his numerous papers published during this period prove his activity in his investigations, and also show that, though engaged on the commercial side of his profession, he never lost his interest in the purely scientific side.

While in France in 1881-1882 Frazer received the degree of Docteur ès-Sciences Naturelles from the Université de France, being the first foreigner to whom this degree had ever been given. It was conferred upon him after a rigid examination and on the presentation of a thesis entitled "Mémoire sur la géologie de la partie sud-est de la Pennsylvanie." In 1890 again the French Government honored him with the title of Officier de l'Instruction Publique.

In 1880-1881 Doctor Frazer was vice-president of the American Institute of Mining Engineers, and in 1907 he was vice-president of the council of the same society. In 1885 he represented the American Association for the Advancement of Science before the Royal Society of Canada, and in the same year he was chosen secretary of the American Committee of the International Geological Congress. In 1888 he was appointed vice-president of the same committee at the meeting of the International Geological Congress held in London that year, and in 1897 he was again chosen vice-president of this committee at the meeting of the International Geological Congress held in Saint Petersburg.

Doctor Frazer was one of the founders of the "American Geologist" and was one of its editors from 1888-1905. In 1889 he was chosen professor of horticultural chemistry by the Horticultural Society of Pennsylvania, another evidence of his diversified talents and interests. In 1896-1898 he was secretary of the American Philosophical Society.

Some of the most active and efficient work of Doctor Frazer's life was done in connection with the Franklin Institute of Philadelphia. In 1882 he was appointed professor of chemistry there, a position that had been held by his father before him. For many years he was one of the editors of the Journal of the Franklin Institute, and was a prolific writer for it on many subjects. He was also one of the board of managers of the institute, and did much to add to its welfare, as well as to the general regard and respect in which it was held by the community. Probably in none of the many fields of his activities did Doctor Frazer do more good than in the Franklin Institute, and his labors in its behalf continued almost up to the day of his death.

Frazer's remarkable facility for letter writing in his own and other languages, and the ease and grace with which he could express himself, made him valuable as a corresponding member of many scientific societies, both in his own country and abroad. He was elected corresponding member of the New York Academy of Sciences in 1885, of the k. k. Geologische Reichanstalt in 1886, of the Sociedad Cientifica "Antonio Alzate" of Mexico in 1891, and honorary member of the Société Géologique de Belgique in 1897.

Doctor Frazer belonged to many scientific and patriotic societies, the diversity of which show his varied interests. He was a fellow of the Geological Society of America, and of the American Association for the Advancement of Science, a member of the American Philosophical Society, Philadelphia Academy of Natural Sciences, Franklin Institute, Pennsylvania Historical Society, Pennsylvania Horticultural Society, American Institute of Mining Engineers, British Association for the Advancement of Science, Société Géologique du Nord (France), Société Géologique de Belgique (Belgium), k. k. Reichsanstalt (Austria), Sociedad Cientifica "Antonio Alzate" (Mexico), Society of American Authors, Military Order of the Loyal Legion, Society of the Cincinnati, Naval Veteran Association, Society of the War of 1812, Society of Colonial Wars in the Commonwealth of Pennsylvania, Pennsylvania Society, Sons of the Revolution, etcetera.

Though geology and chemistry were the branches of science to which Doctor Frazer devoted most of his time, yet in the later years of his life he became noted in his researches in the characteristics of handwriting and the study of manuscript documents, and some of the discoveries he made were original and unique. In 1894 he published a book on "Bibliotics; or, the study of documents," which excited much favorable comment both in this country and abroad. In 1906, in connection with these researches, he was awarded the John Scott medal by the city of Philadelphia for his invention of a colorimeter, or an instrument by which, with the help of certain prisms, he could determine the relative intensity and color value of ink marks in handwriting. Later on he took up the study of the Bertillon system of identification, and visited Bertillon in Europe to discuss his methods with him. He was actively engaged in this work at the time of his death, and in fact his last public address was on this subject in the winter of 1909. His friends noticed at that time that he did not seem well, but he was not considered seriously ill until within a few days of the fatal attack of heart trouble that carried him away.

In 1871 Doctor Frazer married Miss Isabella Nevins Whelen. They had four children—three sons, Persifor, Lawrence, and John, and a daughter, Charlotte. Mrs. Frazer and all the children except Lawrence, who died in childhood, survive him. During the whole of Doctor Frazer's lifetime, after the death of his father, he kept up the Sunday evening gatherings in which the latter had taken so much pleasure, and they were attended both by his father's and his own friends. His intimate friends were not numerous, for he did not court popularity. He was self-reliant and a hard worker, as is shown by his many publications and accomplishments, and most of his time was spent either in the field or in his study.

Dr. John L. Le Conte,[2] in writing in 1873 about the father of Doctor Frazer, described him in the following words, which are also singularly applicable to the son:

> "A man of eminent scientific and general culture; of singular truthfulness of speech, and integrity of conduct; a devoted lover of consistency in action, and strict performance of duty, virtues which he exemplified in himself and sought for in others."

One of Doctor Frazer's most marked traits was his respect for the truth, and when once convinced that his opinion was right, he would brook no opposition, and often caused offense to others by the vigor with which he defended his opinions. But there was no malice in his methods of controversy; he always fought in the open, and the more bitter the argument in which he was involved, the more his opponents realized that they were contending with a strong man, strong in his intellectuality, strong in his convictions, strong in his capacity to fight, seeking for truth as he saw it. Hence, no matter how much they may have differed from him in opinion, they respected his virility and sincerity.

[2] Proceedings of the American Philosophical Society, vol. 13, 1873, pp. 183-190.

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MEMOIR OF DANIEL W. LANGTON, JR.

BY EUGENE A. SMITH

The subject of this sketch was born May 5, 1864, in Mobile county, Alabama. His father, Daniel W. Langdon,[4] Sr., for a number of years had charge of a nursery garden belonging to his uncle, Hon. Charles C. Langdon, at Langdon Station, on the Mobile and Ohio Railroad, a few miles north of Mobile, and was also upon the staff of the Mobile Register. The uncle was a prominent man in State politics for many years, was a member of the legislature, trustee of the A. & M. College, etcetera. The Langdons were of New England extraction, but the uncle and nephew spent most of their lives in Alabama.

Young Langton spent his early years at his father's home at Langdon Station under the tutelage of his mother, a woman of exceptionally wide reading and information. In addition to the formal teaching, she kept him supplied with all available periodicals and magazines, thus developing in him an interest in current events and a taste for general reading which he never lost. As a youth he attended a private school in the city of Mobile kept by Prof. Amos Towle, by whom he was prepared for college. While at school in Mobile young Langton was a member of the household of his kinsman, Col. William A. Buck, whose home was in Summerville, a suburb of Mobile. The Buck family is one of the most cultured and prominent of the older families of this section of the State, and with such surroundings the boy had unusual opportunities for mental development.

In the autumn of 1879 he entered the University of Alabama, from which institution he was graduated with the degree of Bachelor of Arts in 1882. From the same institution he received in 1888 the degree of Master of Arts, and in 1892 that of Doctor of Philosophy.

[4] The family in Alabama spelled the name Langdon, but the subject of this sketch, after he established himself in New York, adopted the spelling Langton, since he found that to be the original spelling of the name.

As a student of the university he was always much interested in the natural sciences, due in great part, no doubt, to his early training in the nursery gardens of his father, for even as a child he was familiar with the names and properties of most of the ornamental and useful plants. Immediately after his graduation, in the summer of 1882, he became associated with the present writer in geological work in the coastal plain of Alabama, which association continued until he finally left the university in 1889. At this time we were engaged in the study of the Tertiary and Cretaceous formations of this section, and many months were spent by us together in examining the banks of the Tombigbee and Alabama rivers, our means of transportation being a skiff paddled by ourselves. After we had established the succession of the strata along these rivers, he carried on the work independently between the Alabama and the Chattahoochee rivers, and on this latter river, in November, 1887, he made the capital discovery of the marine Miocene formations exposed in the bluffs from Chattahoochee Landing to Alum Bluff. To these formations he gave the name Chattahoochee, but later students of this section have restricted the name to the lower beds of the series.

During this period, as his whole time was not given to the Geological Survey, he spent some months in Mexico in the interests of a mining company, and also in the Alabama coastal plain collecting for Mr. Aldrich.

At commencement of 1889 he received the appointment of assistant chemist in the university, the present writer being at that time professor of chemistry and geology. Before the opening of the next college year, however, he received and accepted an offer from the Baltimore and Ohio Railroad to be consulting geologist of that road, so that he did not take up his work in the university.

He remained with the Baltimore and Ohio Railroad as their consulting geologist for about two years, examining and reporting on mineral lands, mainly coal and iron, for this company. In the course of these investigations he became interested in some coal lands in West Virginia, with the result later of developing a property known as the Turkey Knob mine. Of this enterprise he became the manager or superintendent. After a somewhat protracted struggle the mine was compelled to shut down because it was impossible to get from the railroad the cars necessary to handle the output. His experiences here fully convinced him of the fact that a small operator could not get a "fair deal" under the then existing conditions of railroad management. It is possible that the same conditions obtain at the present day.

Leaving West Virginia, he went to New York City, where he opened an office as consulting geologist and engineer. While in this business his attention was directed to landscape architecture, and he gradually drifted into this line of work, for which his early experiences in his father's gardens gave him a natural bias, and he soon rose to eminence in his profession. His first work in this new line was in Princeton, New Jersey, but he always kept his office in New York. His landscape plans were carried out for several estates in the counties of Long Island and in New Jersey and Pennsylvania. He designed and executed the great West Side Park in Jersey City, and also the park at Harrison, New Jersey, both being parts of a scheme of parks in Hudson County, New Jersey. He was a charter member of the American Society of Landscape Architects, which was organized about 1898. In 1901 he went abroad to collect photographs for a book on Italian Gardens which he was to prepare for Forbes & Co., publishers, but by reason of some disagreement between himself and the publishers, he withdrew, and his name did not appear in connection with the book.

Naturally gifted with artistic tastes, these were developed in his landscape work, and after his marriage, in August, 1896, to Berenice Francis, herself an artist and pupil of Rodin and St. Gaudens, their home in New York became a meeting place for artists alike of pen and pencil.

Both Langton and his wife were brilliant talkers, and their associates were all of congenial spirits. After changing his residence to Morristown, New Jersey, where he built a home, he still kept open house for his artist friends, and week-end meetings of these were as a matter of course. His offices remained in the city. With these surroundings, however, he never lost his early love for geology, and he was often heard to wish that he could afford to go back to the old delightful occupation.

He was a firm believer in the power for good of college associations, and was very active in organizing at the University of Alabama the Sigma Nu fraternity, of which he was regent from 1885 to 1890. To the end of his life he took great interest in this fraternity, and attended its meetings whenever it was possible. Along with his interest in the fraternities went a larger interest in university men as such, and we find him a member of the University Club in the cities in which he lived for any length of time.

He was fond of argument and could generally find something to say for his side of the question, and it must be confessed that not infrequently his side would be that opposed to the common opinion. This, together with his usually emphatic way of expressing his views, gained for him the reputation of being somewhat eccentric.

He was a man of strong prejudices, which is about the same as saying he loved his friends and hated his enemies; but for many of his dislikes there seemed, to an onlooker, to be no very special reason. Perhaps it was a case of "Doctor Fell." On the other hand, his friends, or those who knew him intimately, were quite as devoted to him as he was to them.

As a companion in field work he was all that could be desired; his enthusiasm in collecting shells and in the observation of geological phenomena knew no bounds, and it was with difficulty that he could be "moved on" from a good collecting ground. In the trips which he took alone he had many mishaps; he had a faculty for taking the wrong road while driving through the country, often bringing up at the most unexpected places. His inveterate habit of whistling, which absorbed much of his attention, was partly to blame for this; but, in addition to that, his sense of direction or locality was not very highly developed.

In his canoe trips down Cobecuh and Pea rivers, with only a negro man for companion, his boat was capsized a number of times, and on one occasion, on Pea River, everything in the boat was lost, including the gun of his negro companion. On the next day we find the following note, December 12, 1888: "Stephen Wolf, my negro, rendered disconsolate by the loss of his gun, deserted me about 5 p. m., and left me to continue my voyage alone. The river is filled with shoals, and at every shoal there is a fish trap (almost a man trap), and today I crossed no less than twenty-six. Twice today I took involuntary baths, but fortunately nothing but my person was damped, not even my geologic ardor." "Advice to any geologist who in future may contemplate this trip: Don't." This is fairly characteristic of the man; though subject to occasional spells of depression, he was for the most part bright and cheerful, and disposed to look upon the bright side of every question.

When we look upon his career, cut short by an untimely death, and consider that he so soon won his way to eminence in his chosen profession, and that without outside aid and solely by his own exertions, we can not withhold our tribute of respect and admiration.

His death occurred at his home, near Morristown, New Jersey, on the 21st of June, 1909.

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REPORT OF THE COMMITTEE ON THE FORMATION OF THE PALEONTOLOGICAL SOCIETY

The report of the Committee on the Formation of the Paleontological Society was presented through its chairman, W. B. Clark, as follows:

On February 13, 1909, at the American Museum of Natural History, New York City, your committee, composed of W. B. Clark, chairman, and Messrs. H. E. Gregory, J. M. Clarke, and E. O. Hovey, C. W. Hayes being absent, met the Organizing Committee of the Paleontological Society, consisting of Charles Schuchert, chairman, and Messrs. F. B. Loomis, David White, and T. W. Stanton. Messrs. S. W. Williston and H. F. Osborn of the Paleontological Committee were absent. The conferees went over the proposed constitution of the new society article by article, and finally adopted it in the form which was distributed to the Fellows of the Society in March, 1909, and which is appended to this report. (See pages 77-82 of this volume.)

As organized, the Paleontological Society is a section of the Geological Society of America, in accordance with the expressed wish of the majority of paleontologists of the country, and only Fellows of the Geological Society are eligible to Fellowship in the Paleontological Society. Fellows of the Geological Society whose work is primarily in paleontology may become Fellows of the Paleontological Society, on application to the Council of the latter, without further payment of dues. Persons not Fellows of the Geological Society who are engaged or interested in paleontological work may become members of the Paleontological Society by vote of the Society on nomination by two Fellows and approved by the Council.

In order to perfect the affiliation of the new society with the parent organization, certain changes in the Constitution and By-Laws of the Geological Society of America must be made. They are as follows:

Insert Article VIII (new): "SECTIONS. Any group of Fellows representing a particular branch of geology may, with consent of the Council, organize as a section of the Society, with separate constitution and by-laws, provided that nothing in such constitution and by-laws conflicts with the Constitution and By-Laws of the Geological Society of America, in letter or spirit, and provided that such constitution and by-laws and all amendments thereto shall have been approved by the Council."

Change the number of the present Article VIII to IX.

Add to Chapter IV, paragraph 1, this sentence: "One of the nominees for vice-president shall be the nominee for president of the Paleontological Society which has been organized as a section under Article VIII of the Constitution."

This committee having been given power at the Baltimore meeting to act for the Society, the report was, on motion, received and approved.

REPORT OF THE PUBLICATION COMMITTEE

The Publication Committee, through its chairman, E. O. Hovey, then, on call of Vice-President Adams, reported as follows for the information of the Society:

The replies which were received to the circular issued in 1908 regarding editorial usage were carefully compiled and considered, and the following recommendations were made to and adopted by the Council at a meeting held October 14, 1909, at the American Museum of Natural History:

1. That the usage of the Bulletin as to spelling, abbreviation, and punctuation be continued, except that the period be used after all abbreviations, including "Dr." and "Mr.," and that the abbreviation "Jr." and "Sr." be used in place of "Junior" and "Senior" when applied to the name of an individual, and the entire avoidance of the word "Esquire" in connection with the name of an American.

2. Under the head of "capitalization" the adoption of the forms exemplified as follows, although this may lead to some inconsistencies: Lake Superior, Blue Lake, Potomac River, Atlantic Ocean, Mount Taylor, Mount Taylor Range, New York City, Great Neck, Rocky Mountains, Devil's Tower, Summit County, cretacic or Cretaceous.

3. Use of "Cretaceous" and "Carboniferous" and the like, unless the author desires to commit himself to the forms ending in "ic."

4. That authors be allowed to follow the system of capitalization and spelling generally followed as the usage of their particular branches of science.

5. Printing and sending out to the Fellowship simple directions for the preparation of manuscript, which shall embody the preference of the Council as to editorial usage, illustrated with typical examples.

In accordance with the fifth recommendation, the following suggestions for the preparation of manuscripts have been prepared:

The Society's requirements as to the form in which manuscripts should be submitted are so clearly exemplified in the Bulletin itself that it seems almost superfluous to make any suggestions. The following brief summary, however, is offered for the assistance of authors, in accordance with the order employed in the form of publication adopted by the Society.

Title of paper.—The title of a paper should be as brief as is consistent with giving a proper understanding of the subject treated.

It is never necessary to rewrite a paper in the title, and elaborateness rarely adds sufficiently to clearness to warrant its use.

The employment of articles before the title should be avoided.

Name of the author.—Following the title, but in a separate line, should appear the name of the author, preceded by the word "By."

Presentation before the Society.—The next line should state whether the paper was "Read before the Society," "Presented extemporaneously," "Presented in abstract," or "Presented by title before the Society," being careful to add the date of reading or presentation.

Contents.—A table of contents must be prepared by the author, showing the order in which the subject-matter of the paper has been treated. Such a table of contents is the test of the logical preparation and presentation of a paper.

Captions.—The Society has adopted four captions, the first of which is centrally placed and printed in capitals and small capitals; the second is in italicised capitals centrally placed; the third is a side or paragraph heading printed in italics, and the fourth is a side heading in Roman type.

Under each of the first three headings there should be at least two headings of the next order of inferiority to warrant the use of the latter. For instance, authors will frequently use a superior heading and then under it place only one inferior heading. Manifestly, these two should be combined in one caption appropriately referring to the next which follows.

Footnotes.—Consecutive Arabic numerals should be used for the indication of footnotes, beginning with "1," and the footnote should be inserted wherever it may come on the typewritten page, with a ruled or dotted line immediately above and below it.

Illustrations.—Two classes of illustrations are employed in the Bulletin—text figures and half-tone plates. The former are numbered from 1 upward in each brochure, so that the numbering adopted by the author is not disturbed. The latter, however, have consecutive numbering for the entire volume; hence an author should give each plate a tentative designation, such as A, B, C. This designation will be replaced by the correct plate number and the author given an opportunity to verify references. The plates are made up of one or more figures. When more than one figure occurs on the page the first is designated "Figure 1," followed by the appropriate title; the second "Figure 2," etcetera. In addition to this, the plate has a general title or plate title descriptive of all the figures. An exception is made sometimes in the matter of titling plate figures, when there are many illustrations to the page, as in plates of fossils. In such cases a full description of the figures is usually printed on a separate page facing the plate, all such plates being placed at the end of the brochure. As all the text figures and all plates are scheduled in the "preliminary matter" which precedes each volume, the desirability of making captions as brief as is consistent with clearness is apparent.

More comprehensive suggestions, which meet the general approval of the Society's Council, are contained in the "Suggestions to Authors," compiled for the United States Geological Survey by George McLane Wood. A copy of this pamphlet has been sent to every Fellow of the Geological Society of America, and careful study of its recommendations is urged on all those preparing papers to be offered for publication in the Bulletin.

Papers should always be submitted in typewriting.

On motion, the report was ordered printed in full.

The committee reports further that the Council, at the meeting of October 14, 1909, voted to change the manner of issuing the Bulletin to quarterly form, beginning March, 1910, with Part I of Volume XXI, doing away with both the brochure form and the collated volume, except that author's separates of the different memoirs will be issued like the former brochures, thirty of which will be given gratis to authors, as heretofore, and a supply will be retained by the Secretary to meet the demand for single articles. The change to a quarterly issue has been made to facilitate publication and to take advantage of entry in the post-office as second-class matter, thereby effecting a material saving in the expense of distribution.

AMENDMENTS TO THE CONSTITUTION AND BY-LAWS

The Secretary then announced that more than three-fourths of the Fellows of the Society had voted in favor of the amendments to the Constitution which had been proposed in due form in March, 1909, and that they therefore were operative. They are those referred to in the report of the Committee on the Formation of the Paleontological Society and are as follows:

Insert Article VIII (new): "SECTIONS. Any group of Fellows representing a particular branch of geology may, with consent of the Council, organize as a section of the Society with separate constitution and by-laws, provided that nothing in such constitution and by-laws conflicts with the Constitution and By-Laws of the Geological Society of America, in letter or spirit, and provided that such constitution and by-laws and all amendments thereto shall have been approved by the Council."

Change the number of the present Article VIII to IX.

Vice-President Adams then called for a vote on the amendment to the By-Laws, which had been proposed in due form in the Secretary's March circular, as follows:

Add to Chapter IV, paragraph 1, this sentence: "One of the nominees for vice-president shall be the nominee for president of the Paleontological Society which has been organized as a section under Article VIII of the Constitution."

On motion, this amendment was unanimously adopted.

REPORT OF THE PHOTOGRAPH COMMITTEE

A report from the Photograph Committee was then called for, but was not presented on account of the absence of N. H. Darton, who constitutes the committee.[5]

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[5] Since the close of the meeting the report has been transmitted to the Secretary, and is as follows:

TWENTIETH ANNUAL REPORT OF THE COMMITTEE ON PHOTOGRAPHS

During the year 1909 there has been no change in the collection of photographs belonging to the Society. No new views have been offered. Several members have inspected the collection, and ordered prints from negatives belonging to the United States Geological Survey.

The collection is stored in a chest and bundle in my office in the building of the Geological Survey at Washington, where it can be readily consulted.

Respectfully submitted. N. H. DARTON,
Committee.

Announcements regarding the arrangements effected by the Local Committee were then made by the Secretary.

TITLES OF PAPERS AND NAMES OF DISPUTANTS

The general business of the morning having been finished, the program of scientific papers relating to glaciology and physiography was taken up as follows:

POST-TERTIARY HISTORY OF THE LAKES OF ASIA MINOR AND SYRIA

BY ELLSWORTH HUNTINGTON

Presented extemporarily; illustrated with lantern slides; 25 minutes. Discussed by W. M. Davis, F. P. Gulliver, A. W. Grabau, D. W. Johnson, and Joseph Barrell, with reply by the author.

TIDE-WATER GLACIERS OF PRINCE WILLIAM SOUND AND KENAI PENINSULA, ALASKA

BY U. S. GRANT

In the absence of the author, the paper was read by title.

OSCILLATIONS OF ALASKAN GLACIERS

BY R. S. TARR AND LAWRENCE MARTIN

Presented extemporarily by the junior author; illustrated with lantern slides; 20 minutes. Discussed by François E. Matthes.

SOME EFFECTS OF GLACIER ACTION IN ICELAND

BY FRED E. WRIGHT

Read from manuscript; 15 minutes. Discussed by W. M. Davis.

CLIFF SCULPTURE OF THE YOSEMITE VALLEY

BY FRANÇOIS E. MATTHES[6]

Read in part from manuscript and in part presented extemporarily with lantern slide illustrations; 30 minutes.

EOLATION UNDER THE STIMULUS OF ARIDITY

BY CHARLES R. KEYES

Read by title in the absence of the author.

At 12.30 o'clock p. m. the Society adjourned for luncheon at the Colonial Club, convening again at 2.30 p. m. in two sections for the reading of

[6] Introduced by M. R. Campbell.

papers. The glacial and physiographic papers were continued under the temporary chairmanship of H. L. Fairchild, F. B. Taylor acting as secretary of the section.

FURTHER LIGHT ON THE GORGE OF THE HUDSON

BY JAMES F. KEMP

Given extemporaneously; illustrated with drawings; 20 minutes. The paper was discussed by J. W. Spencer, with reply by the author.

RICHMOND BOULDER TRAINS

BY F. B. TAYLOR

Presented extemporaneously; illustrated with lantern slides; 15 minutes.

GLACIAL LAKES AND CHANNELS NEAR SYRACUSE

BY T. C. HOPKINS

Read by title, the author being absent.

SHORELINES OF THE GLACIAL LAKES IN THE OBERLIN QUADRANGLE, OHIO

BY FRANK CARNEY

Given extemporarily; illustrated with map and lantern slides; 15 minutes.

ISOBASES OF THE ALGONQUIN AND IROQUOIS BEACHES AND THEIR SIGNIFICANCE

BY JAMES WALTER GOLDTHWAIT[7]

Read from manuscript; illustrated with lantern slides; 20 minutes. The paper was discussed by J. W. Spencer, Frank Carney, and F. B. Taylor. Reply was made by the author.

GLACIAL INVESTIGATIONS IN THE LAKE SUPERIOR REGION IN 1909

BY FRANK LEVERETT

Read by title in the absence of the author.

DIVERSION OF THE MONTREAL RIVER

BY ROBERT BELL

Presented extemporaneously and illustrated with a map; 25 minutes.

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[7] Introduced by F. B. Taylor.

RELATIVE WORK OF THE TWO FALLS OF NIAGARA

BY J. W. SPENCER

Given extemporarily; 20 minutes.

At 5 o'clock the section adjourned.

The main division of the Society met, under the chairmanship of Vice-President Adams, Tuesday afternoon, in the Nash Botanical Lecture Room of the Museum, and began the consideration of the papers in physical and structural geology.

NATURAL BRIDGES OF NORTH AMERICA, WITH A DISCUSSION OF THEIR ORIGIN

BY HERDMAN F. CLELAND

Presented extemporaneously; illustrated with lantern slides; 20 minutes. Discussed by H. C. Hovey and J. W. Spencer.

GEOLOGICAL SUGGESTIONS DERIVED FROM A NEW ARRANGEMENT OF THE ELEMENTS

BY B. K. EMERSON

Given extemporaneously; illustrated with diagrams; 30 minutes.

NEW LIGHT ON THE GEOLOGY OF THE WASATCH MOUNTAINS

BY ELIOT BLACKWELDER

Presented extemporaneously; illustrated with lantern slides; 35 minutes. Discussed by S. F. Emmons, Bailey Willis, A. W. Grabau, Arthur Keith, and the author.

HAWAIIAN VOLCANOES

BY REGINALD A. DALY

Presented without notes; illustrated with lantern slides; 25 minutes. Discussed by T. A. Jaggar, Jr.

The main section adjourned at 5 o'clock.

Tuesday evening the Society met in the rooms of the Technology Union and participated in a smoker as the guests of the Department of Geology of the Massachusetts Institute of Technology. The attendance was large and the occasion was most enjoyable.

Session of Wednesday, December 29

Wednesday morning the Society was called to order in the Geological Lecture Hall at 9.45 o'clock by Vice-President Adams.

REPORT OF THE AUDITING COMMITTEE

The report of the Auditing Committee being called for, it was presented by F. L. Ransome, to the effect that the Treasurer's accounts had been examined and found to be correctly cast and properly vouched, and that the committee would visit Baltimore at an early date and verify the securities in the custody of the Treasurer.[8]

On motion, the report was accepted.

TITLES OF PAPERS AND NAMES OF DISPUTANTS

After sundry announcements had been made by the Secretary, the reading of papers was resumed, and the audience listened to

GENETIC CLASSIFICATION OF ACTIVE VOLCANOES

BY T. A. JAGGAR, JR.

which was read from manuscript, occupying 20 minutes. This was followed by

TARUMAI, A CUMULO-VOLCANIC ERUPTION IN JAPAN, 1909

BY T. A. JAGGAR, JR.

Given without notes; illustrated with lantern slides; 15 minutes. The discussion of the two papers was participated in by E. O. Hovey, W. M. Davis, F. L. Ransome, R. A. Daly, Bailey Willis, F. E. Wright, Ernest Howe, and the author.

ALASKAN EARTHQUAKE OF 1899

BY LAWRENCE MARTIN

Presented extemporaneously; illustrated with lantern slides; 10 minutes.

STRUCTURE OF THE NORTHERN PORTION OF THE BURNING SPRINGS, VOLCANO ANTICLINE, IN PLEASANTS, WOOD, AND RITCHIE COUNTIES, WEST VIRGINIA

BY F. G. CLAPP

Read from manuscript; 10 minutes. Discussed by I. C. White.

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[8] Since the close of the meeting the committee has reported to the Secretary that Messrs. Ransome and Emmons visited Baltimore, according to instructions from the Society, and found the securities in the possession of the Treasurer to correspond with the list reported by him.

GENERALIZED SECTION THROUGH THE APPALACHIAN MOUNTAINS OF MARYLAND

BY CHARLES K. SWARTZ

Read from manuscript; illustrated with maps and sections. Discussed by Arthur Keith, A. H. Purdue, and the author.

The morning session adjourned at noon.

The afternoon meeting was in two parts, the main section continuing the consideration of the papers on physical and structural geology in the Geological Lecture Hall, while the second section met in the Mineralogical Laboratory, and proceeded with the reading of the papers on glacial and physiographic geology.

In the main section the following papers were called:

SOME INSTANCES OF FLOWING WELLS ON ANTICLINES

BY F. G. CLAPP

Read from manuscript; 10 minutes. Discussed by A. C. Lane.

LOCAL ANTICLINES IN THE CHAGRIN SHALES AT CLEVELAND, OHIO

BY FRANK R. VAN HORN

Presented extemporaneously and illustrated with lantern slides; 20 minutes. The paper was discussed by H. L. Fairchild.

President-elect Arnold Hague then took the chair, while a paper entitled "An experimental investigation into the flow of diabase" was presented extemporarily by F. D. Adams, with lantern slide illustrations, in 20 minutes. The paper was discussed by H. F. Reid, Bailey Willis, and the author.

Vice-President Adams resumed the chair, and the following paper was read by title in the absence of the author:

COON BUTTE AND METEORITIC FALLS OF THE DESERT

BY CHARLES R. KEYES

Then was presented extemporaneously

CONNATE WATERS OF THE ATLANTIC COAST

BY ALFRED C. LANE

occupying 20 minutes.

After this

CHANGES PRODUCED ON SPRINGS BY A SINKING WATER TABLE

BY T. C. HOPKINS

was given without notes; 10 minutes.

There was then read a paper entitled

CRITERIA FOR THE RECOGNITION OF VARIOUS TYPES OF SAND GRAINS

BY W. H. SHERZER

The reading was followed by the presentation of illustrative lantern slides; 20 minutes. The discussion that followed was participated in by Joseph Barrell, A. C. Lane, and W. M. Davis.

The next paper

CLIMATE AND PHYSICAL CONDITIONS OF THE KEEWATIN

BY A. P. COLEMAN

was presented without notes, in 20 minutes, and was discussed by W. G. Miller, H. F. Reid, W. M. Davis, and the author.

With permission from the Society, an overture from the American Philosophical Society was then read, asking for encouragement of a plan for American exploration in the Antarctic regions.

On motion, the communication was referred to the Council for consideration and report back to the Society.

Then was presented from notes

THEORY OF ISOSTACY

BY W. M. DAVIS

in 15 minutes. The paper was discussed by H. F. Reid.

The last paper of the afternoon was

MECHANICS OF FAULTS

BY HARRY FIELDING REID

Presented extemporaneously; 20 minutes.

The section adjourned at 5 o'clock.

The section of glacial and physiographic geology began the afternoon session with H. L. Fairchild in the chair and F. B. Taylor acting as secretary.

The first paper was

RELATIONSHIP OF NIAGARA RIVER TO THE GLACIAL PERIOD

BY J. W. SPENCER

Presented without notes; illustrated with lantern slides; 20 minutes. Discussed by Lawrence Martin, F. B. Taylor, W. M. Davis, and the author.

PARTIAL DRAINAGE OF NIAGARA FALLS IN FEBRUARY, 1909

BY J. W. SPENCER

Presented extemporaneously; illustrated with lantern slides; 10 minutes.

BIRD'S HILL: AN ESKER NEAR WINNIPEG, MANITOBA

BY WARREN UPHAM

Read by title in the absence of the author.

ORIGIN OF CLIFF LAKE, MONTANA

BY G. R. MANSFIELD[9]

Read from manuscript; illustrated with lantern slides; 20 minutes. Discussed by W. M. Davis and the author.

ROCK STREAMS OF VETA MOUNTAIN, COLORADO

BY H. B. PATTON

Presented extemporaneously; illustrated with lantern slides; 20 minutes. Discussed by D. W. Johnson, F. E. Matthes, W. M. Davis, and the author.

The next two papers were presented without notes. They were entitled

MEANDERS AND SCALLOPS

BY M. S. W. JEFFERSON

Illustrated with lantern slides; 15 minutes.

BEACH CUSPS

BY M. S. W. JEFFERSON

Fifteen minutes.

[9] Introduced by U. S. Grant.

They were followed by

BEACH CUSPS

BY D. W. JOHNSON

Given extemporaneously; illustrated with lantern slides; 20 minutes. The section adjourned at 5 o'clock.

Wednesday evening the Fellows of the Geological Society of America and of the Paleontological Society, the members of the latter and friends, in all 131 persons, took part in the customary annual dinner, which was held in the Hotel Vendome, Boston. The meeting was presided over by Vice-President Adams, who, before general speaking began, called upon President-elect Hague to read the following communication which had been received from President Gilbert:

"To the Fellows of the Geological Society of America I send a cordial greeting. Though physically separate, I am one with you in motive and enthusiasm.

"Keenly as I should enjoy the intellectual interchange and the social joys of our assemblage, keenly as I regret my inability to assume the duties properly joined to the high honor you have bestowed on me, yet am I not without consolation. For I know well that other hands, willing and able, will perform whatever I have left undone, that the lusty vigor of our Society ensures the quick closing of every gap, and that the cherished cause for which our association stands is imperiled by no default of an individual.

"As thought roams backward over the long series of our fruitful meetings, I realize as never before how the growth of our science has been interwoven with the growth of our organization, how our individual efficiency and our associative efficiency have each enhanced the other, and how the harmony and solidarity of our geologic body have been fostered by the personal contact of its members.

"As I dwell with longing on all the privileges that this week are yours, I realize more than ever before how strong are the personal ties which bind me to you and how large a measure of real comradeship has come to be implied by our formal title of Fellow. And so, Fellows of the Geological Society, I send a more than cordial—I send an affectionate greeting.

"G. K. GILBERT.

"WASHINGTON, *December* 26, 1909."

On motion of Second Vice-President Clarke, the Secretary was unanimously instructed to send the following telegraphic reply to Mr. Gilbert:

"29 DECEMBER, 1909.

"MR. GROVE K. GILBERT, *Washington, D. C.:*

"We, Fellows of the Geological Society, assembled at the Annual Dinner, return your greeting and express our sincere regret at your absence. We assure you of our cordial personal interest and sympathy and of our hope to have you with us soon again.

"EDMUND OTIS HOVEY, *Secretary.*"

Then, after a graceful speech of welcome to the Society and guests, Doctor Adams called upon James F. Kemp to act as toastmaster. This service was rendered in a happy vein of humor that thoroughly satisfied the company, as one after another eight or ten Fellows responded to the summons of the toastmaster. The evening was further enlivened by occasional singing by the diners from a "Geological Song Book," which had been compiled and provided by A. C. Lane. A cordial letter was prepared, signed by all present and subsequently sent to Professor Eduard Suess, of Vienna, congratulating him on the completion of his monumental work "Das Antlitz der Erde."[10] C. H. Warren was the member of the Local Committee who had charge of the arrangement for the dinner.

Session of Thursday, December 30

Thursday morning the Society was called to order in general session at 9.45 o'clock by Vice-President Adams, in the Geological Lecture Hall of the University Museum. The printed report of the Council, which had just arrived, was distributed, but action upon it was deferred to the afternoon.

RESOLUTION CONCERNING ANTARCTIC RESEARCH

The Secretary then reported that the Council had considered with approval the preamble and resolutions submitted by the American Philosophical Society, and recommended their adoption. They are as follows:

"Whereas the United States in former years did much to increase our knowledge of the Antarctic regions, by means of the expedition of Lieut. Charles Wilkes, U. S. N., and the voyages of American whalers, and

"Whereas there has been a great revival of interest in recent years in the South Polar regions, resulting in the dispatching of scientific expeditions to explore portions of this area by England, Belgium, Sweden, Germany, and France, and

---

[10] The following reply to this communication has been received by the Secertary:

VIENNA, *March* 4, 1910.

DEAR SIR: I am indeed at a loss in trying to describe the feeling which pervaded me in receiving the testimonial letter and congratulation of the Geological Society of America. If my book possesses some merit, it consists in showing how very narrow the limits of our actual knowledge of the earth are, and if anything is apt to bid glad hopes, it is the brilliant list of one hundred and ten great masters and ardent scholars trying to unravel the structure of your vast and diversified country, who have honored me in this extraordinary way.

I beg to transmit my heartfelt thanks to all these gentlemen and colleagues in science and my respectful compliments to President Gilbert.

Your deeply obliged,

E. SUESS.

"Whereas large areas in the far South will remain unexplored and many branches of science would be benefited by the sending of an American expedition to the far South, having for its object the re-exploration of Wilkes Land and the collection of scientific data relating to regions visited, therefore be it

"*Resolved*, That the Geological Society of America respectfully urges the Federal Government to consider the desirability of appropriating funds for the purpose of fitting out a suitable vessel, under the direction of the Secretary of the Navy, to undertake such exploration."

On motion, the resolution was passed.

REPORT OF THE COMMITTEE ON GEOLOGIC NOMENCLATURE

The Committee on Geologic Nomenclature then reported, through Arthur Keith, its secretary, that requests for suggestions had been sent out early in the year and some replies received, but that no questions had been submitted to the consideration of the committee. On motion, the report was received and the committee continued.

REPORT OF THE COMMITTEE ON THE NOMENCLATURE OF FAULTS

The Committee on the Nomenclature of Faults reported, through its chairman, H. F. Reid, that correspondence had been carried on with the Geological Society of London and other bodies, with not wholly satisfactory results, but that the work was progressing. On motion, the report was received and the committee continued.

TITLES OF PAPERS AND NAMES OF DISPUTANTS

The paper entitled

A PROGRESS GEOLOGIC MAP OF OKLAHOMA

BY C. N. GOULD

was then presented extemporarily, illustrated with a large map; 15 minutes. It was discussed by Arthur Keith.

The next paper was read from manuscript. It was

SALT MARSH FORMATION NEAR BOSTON AND ITS GEOLOGICAL SIGNIFICANCE

BY CHARLES A. DAVIS[11]

Twenty minutes. Remarks were made by A. W. Grabau.

Then was presented from notes and illustrated with lantern slides a paper entitled

OBSERVATIONS ON RATE OF SEA CLIFF EROSION

BY CHARLES P. BERKEY

Fifteen minutes.

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[11] Introduced by David White.

The Society then divided again into two parts, the stratigraphic and paleontologic section remaining in the large lecture hall, while the main body went into the laboratory of the Department of Mineralogy. The chairman of the section was President-elect Hague, while the Secretary, during the presentation of the first four papers, was H. B. Kümmel, and afterwards C. N. Gould.

In the absence of the author, the paper entitled

RED SANDSTONES OF SOUTHEASTERN MINNESOTA

BY C. W. HALL

was read by title.

Then

PERMO-CARBONIC CONGLOMERATES OF SOUTH BRAZIL

BY J. B. WOODWORTH

was presented extemporaneously from notes, illustrated with lantern slides; 45 minutes. Discussed by Bailey Willis and I. C. White.

Adjourned at noon for luncheon, and reconvened at 2.30 o'clock p. m.

MAGOTHY FORMATION OF THE ATLANTIC COAST

BY A. B. BIBBINS

was read by title, the author being absent.

After this

AGE OF THE "CALCIFEROUS" FORMATIONS OF THE MOHAWK VALLEY

BY E. O. ULRICH AND H. P. CUSHING

was given extemporaneously by Professor Cushing; 15 minutes.

The paper entitled

UPPER CAYUGAN OF MARYLAND

BY T. POOLE MAYNARD[12]

was then read from manuscript; 15 minutes. Discussed by A. W. Grabau.

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[12] Introduced by W. B. Clark.

Then the paper

STRATIGRAPHIC RELATIONS OF THE LIVINGSTON BEDS OF CENTRAL MONTANA

BY R. W. STONE AND W. B. CALVERT[13]

was read from manuscript by Mr. Stone; 30 minutes.

After this the following papers were read by title in the absence of their authors:

DISCOVERY OF FOSSILS IN THE QUANTICO SLATE BELT AND THE ASSOCIATION OF VOLCANO-SEDIMENTARY BEDS WITH THE SLATES OF THE VIRGINIA CRYSTALLINE REGIONS

BY T. L. WATSON AND S. L. POWELL

PLEISTOCENE PHENOMENA OF CENTRAL MASSACHUSETTS

BY W. C. ALDEN

REVISION OF PALEOZOIC SYSTEMS, II

BY E. O. ULRICH

EVIDENCE THAT THE FOSSILIFEROUS GRAVEL AND SAND BEDS OF IOWA AND NEBRASKA ARE AFTONIAN

BY B. SHIMEK

NOTE ON A METHOD IN TEACHING OPTICAL MINERALOGY

BY F. W. MC NAIR[14]

PEBBLES: TYPES FORMED BY THE SEA, RIVERS, WIND, AND GLACIERS

BY F. P. GULLIVER

RHODE ISLAND COAL

BY CHARLES W. BROWN

PREGLACIAL DRAINAGE OF CENTRAL WESTERN NEW YORK

BY A. W. GRABAU

At 4 o'clock the section adjourned.

After the separation into sections the main body of the Society, under the chairmanship of Vice-President Adams, listened to the papers in the

[13] Introduced by M. R. Campbell.
[14] Introduced by Alfred C. Lane.

petrologic, mineralogic, and economic subdivision of the program, the first paper being read from manuscript. It was

GEOLOGIC THERMOMETRY

BY FRED E. WRIGHT

Fifteen minutes. Remarks upon the paper were made by J. F. Kemp, R. A. Daly, A. C. Lane, and E. T. Wherry.

Then was presented extemporaneously

SOME MINERAL RELATIONS FROM THE LABORATORY VIEWPOINT

BY ARTHUR L. DAY

Twenty minutes. Discussion was postponed to the afternoon session, and the Society adjourned at 12.15 for luncheon, convening again at 2 o'clock, when the discussion of Doctor Day's paper was taken up and participated in by A. C. Gill, Whitman Cross, and the author.

After this

ORIGIN OF THE ALKALINE ROCKS

BY REGINALD A. DALY

was read in abstract from the complete manuscript, 25 minutes, and was discussed by J. F. Kemp, Whitman Cross, H. P. Cushing, A. E. Barlow, W. G. Miller, and the author.

Then was presented extemporaneously

THE COMPLEX OF ALKALINE IGNEOUS ROCKS AT CUTTINGSVILLE, VERMONT

BY J. W. EGGLESTON[15]

illustrated with diagrams and specimens. The paper was discussed by J. E. Wolff, F. E. Wright, and J. A. Dresser.

The next paper

OBSIDIAN FROM HRAFNTINNUHRYGGUR, ICELAND

BY FRED E. WRIGHT

was given without notes, and was illustrated with a suite of specimens; 5 minutes.

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[15] Introduced by J. E. Wolff.

Following this, the paper entitled

BLEACHING OF GRANITE AT LIMESTONE CONTACTS

BY H. P. CUSHING

was presented extemporarily, illustrated with specimens; 15 minutes.

Then the joint paper

PEGMATITE IN THE GRANITE OF QUINCY, MASSACHUSETTS

BY C. H. WARREN AND C. PALACHE

was divided into two parts, the discussion of the petrography being read from manuscript by Professor Warren, while the mineralogical portion was presented extemporaneously by Professor Palache, using a large series of specimens as illustrations. Remarks were made by J. F. Kemp.

BARITE DEPOSITS OF FIVE ISLANDS, NOVA SCOTIA

BY CHARLES H. WARREN

was presented by title.

FAYALITE IN THE GRANITE OF ROCKPORT, MASSACHUSETTS

BY CHARLES PALACHE

was given without manuscript, and consisted of an exhibition of specimens with a description of their mode of occurrence; 10 minutes.

NELSONITE: A NEW ROCK TYPE, ITS OCCURRENCE, ASSOCIATION, AND COMPOSITION

BY T. L. WATSON AND S. TABER

was read by title in the absence of the authors.

MICROSCOPIC STUDY OF CERTAIN COALS IN RELATION TO THE SAPROPELIC HYPOTHESIS

BY E. C. JEFFREY[16]

was presented extemporaneously with numerous lantern slide illustrations, 30 minutes. Remarks on the paper were made by David White.

REGIONAL DEVOLATILIZATION OF COAL

BY DAVID WHITE

was given without manuscript, 15 minutes, and was discussed by J. F. Kemp.

[16] Introduced by David White.

The last paper on the program was

PRESENT AND FUTURE OF NATURAL GAS FIELDS IN THE NORTHERN APPALACHIANS

BY F. G. CLAPP

which was read from manuscript, 20 minutes, and was discussed by J. F. Kemp and F. R. Van Horn.

After the presentation of Professor Jeffrey's paper the scientific program was interrupted for the consideration of some matters of business. The Council report was taken from the table, and on motion was accepted and ordered printed. It will be found on pages 35-39 of this volume.

Whitman Cross then offered a vote of thanks to the Governing Board of Harvard University for the courtesies of the University Museum and to the geologists and mineralogists of Harvard University and the Massachusetts Institute of Technology for the completeness of the arrangements made for the meetings. The motion was seconded by James F. Kemp, and was heartily passed by the Society.

Sessions of the Paleontological Section, December 29, 30, and 31

The section of the Geological Society of America which had been organized under section VIII of the Constitution as amended in 1909 met in the Nast Lecture Hall of the Harvard University Museum on Wednesday, Thursday, and Friday, December 29-31, 1909, with John M. Clarke as President and H. F. Cleland as Secretary. An account of the meeting will be found on pages 69-76 of this volume.

Cordilleran Section

In accordance with a request received from the Council of the Cordilleran Section, the General Council voted that the sectional meeting might be postponed from convocation week to the latter part of February or March.

Report of the Council

To the Geological Society of America,
in Twenty-second Annual Meeting assembled:

The regular annual meeting of the Council was held at Baltimore, Maryland, in connection with the meeting of the Society, December 29, 1908, to January 1, 1909. An adjourned meeting was held in New York city on October 14, 1909, and some business has been transacted by correspondence.

The details of administration for the twenty-first year of the existence of the Society are given in the following reports of the officers:

Secretary's Report

To the Council of the Geological Society of America:

Meetings.—The proceedings of the annual meeting of the Society held at Baltimore, Maryland, December 29, 1908, to January 1, 1909, have been recorded in the closing brochure of volume 20 of the Bulletin, which is now in press.

Membership.—During the past year the Society has lost two Fellows by death, Persifor Frazer and Daniel W. Langton, and one member has been dropped on account of non-payment of dues. The names of the fourteen Fellows elected at the Baltimore meeting have been added to the list, all of them having completed their membership according to rule. The present enrollment of the Society is 305. Twenty-four candidates are before the Society for election, and several applications are under consideration by Council.

Distribution of Bulletin.—There have now been distributed 9 brochures, comprising 356 pages, of volume 20, and the remaining brochures, including the Proceedings, are in the hands of the printers in various stages of completion. By action of the Publication Committee no manuscripts were accepted by the Secretary after October 1.

There are now 95 regular subscribers for the Bulletin and 75 institutions that receive the publication on exchange.

The irregular distribution of the Bulletin during the past year has been as follows: Complete volumes, sold to the public, including one complete set, 30; sent out to supply delinquents, 12; sent out to supply deficiencies, 4; brochures sent out to supply deficiencies and delinquents, 189; sold to Fellows, 15; sold to the public, 48. Three copies of volume 19 have been bound for the use of the officers and the library.

Bulletin Sales.—The receipts from the sale of the Bulletin during the past year are shown in the following table:

Bulletin Sales, December 1, 1908, to November 30, 1909

	Complete volumes.			Brochures.			Grand total.
	Fellows.	Public.	Total.	Fellows.	Public.	Total.	
Volume 1	....	$7.50	$7.50	$0.25	$7.05	$7.30	$14.80
Volume 2	....	15.00	15.00	.25	.40	.65	15.65
Volume 3	....	15.00	15.00	....	.45	.45	15.45
Volume 4	....	7.50	7.50	....	4.40	4.40	11.90
Volume 5	....	7.50	7.50	.20	1.30	1.50	9.00
Volume 6	....	7.50	7.50	.35	.75	1.10	8.60
Volume 7	4.00	7.50	11.50	.55	....	.55	12.05
Volume 8	4.00	7.50	11.50	....	.35	.35	11.85
Volume 9	....	7.50	7.50	1.25	.35	1.60	9.10
Volume 10	4.00	7.50	11.50	1.70	2.10	3.80	15.30
Volume 11	....	7.50	7.50	2.45	....	2.45	9.95
Volume 12	....	7.50	7.50	1.50	.55	2.05	9.55
Volume 13	....	7.50	7.50	1.20	....	1.20	8.70
Volume 14	....	7.50	7.50	....	....	....	7.50
Volume 15	....	7.50	7.50	1.50	.55	2.05	9.55
Volume 16	....	7.50	7.50	2.20	2.20	4.40	11.90
Volume 17	....	7.50	7.50	3.80	3.60	7.40	14.90
Volume 18	....	27.50	27.50	1.75	12.95	14.70	42.20
Volume 19	5.00	165.00	170.00	4.52	3.40	7.92	177.92
Volume 20	....	480.00	480.00	....	7.20	7.20	487.20
Volume 21	....	37.50	37.50	....	....	....	37.50
	$17.00	$852.50	$869.50	$23.47	$47.60	$71.07	$940.57
Balance on 1908 report							.05
Collection charges added to checks							.52
							$941.14

Receipts for the fiscal year	$940.62
Previously reported	11,245.51
Total receipts to date	$12,186.13
Charged, but not yet received :	
On 1909 account	28.80
Total sales to date	$12,214.93

The bills for volume 20 have not been sent out to volume subscribers who do not pay in advance, and the table given above includes only actual payments.

The cost of publishing the Bulletin, volumes 1–19, has been $35,296.10, the average cost per volume being $1,857.69. These figures, however, do not include the expense of distribution. The expense of publication has increased so much during the past few years that the price of the Bulletin to libraries and foreign individuals has been raised to $7.50 per volume by vote of Council.

Expenses.—The following table gives the cost of administration and of Bulletin distribution during the past year:

EXPENDITURE OF SECRETARY'S OFFICE DURING THE FISCAL YEAR ENDING NOVEMBER 30, 1909

Account of Administration

Postage and telegrams	$49.13	
Express	4.43	
Stationery and printing	181.70	
Addressograph plates	.72	
Stenographer at 1908 meeting	150.00	
Lantern operator at 1908 meeting	6.00	
Labor and materials	9.15	
Binding	3.50	
Expenses of Cordilleran Section	7.97	
Expenses of Paleontological Society	56.83	
Total		$469.43

Account of Bulletin

Postage	$132.39	
Express	39.20	
Collection on checks	1.50	
Labor and materials	1.05	
Stationery and printing	21.95	
Binding	1.00	
Total		$197.09
Total expenses for the year		$666.52

Respectfully submitted.

EDMUND OTIS HOVEY,
Secretary.

NEW YORK, *December 15, 1909.*

TREASURER'S REPORT

To the Council of the Geological Society of America:

The Treasurer herewith submits his annual report for the year ending December 1, 1909:

Eight (8) Fellows, Charles Schuchert, H. V. Winchell, Earle Sloan, Eliot Blackwelder, H. E. Gregory, G. B. Richardson, Ralph Arnold, and Edward B. Mathews, have commuted for life during the year by the payment of one hundred dollars each, thus increasing the total Life Commutations to ninety-three (93), which with four (4) Honorary

Life Members, makes a total of ninety-seven (97), of whom eighty-eight (88) are now living.

Two (2) Fellows are delinquent for four years, one (1) Fellow is delinquent for three years, two (2) Fellows are delinquent for two years, and are therefore liable to be dropped from the roll for non-payment of dues, in accordance with section 3, chapter 1, of the By-Laws; twelve (12) Fellows are delinquent for the present year.

The membership of the Society, including delinquents, aggregates at the present time 305, of whom 88 have commuted for life. There have been two deaths and one member has been dropped for non-payment of dues.

RECEIPTS

Balance in treasury December 1, 1909		$795.83	
Fellowship fees 1906 (3)	$30.00		
" " 1907 (10)	100.00		
" " 1908 (24)	240.00		
" " 1909 (198)	1,980.00		
		2,350.00	
Initiation fees (14)		140.00	
Life commutations (8)		800.00	
Interest on investments:			
Iowa Apartment House Company	$60.00		
Ontario Apartment House Company	200.00		
Texas and Pacific Railroad bonds	100.00		
United States Steel Corporation bonds	150.00		
St. Louis, Iron Mountain and Southern Railroad bonds	50.00		
Interest on deposits in Baltimore Trust and Guarantee Co	27.01		
		587.01	
Received from Secretary:			
Sales of publications		940.62	
Subscriptions toward publication of papers:			
J. C. Branner		50.00	
Charles Schuchert		59.77	
Authors' corrections (paid by authors)		2.10	
Collection charges added to checks		.52	
Stenographer's report (paid by A. A. A. S.)		54.80	
Collection charges added to checks		.40	
Received from J. C. Merriam (afterward refunded)		70.00	
			$5,851.05

EXPENDITURES

Secretary's office:				
Administration	$412.60			
Bulletin	197.09			
Paleontological Society	56.83			
Secretary's allowance	500.00			
		$1,166.52		
Treasurer's office:				
Postage, bond, safe deposit, etcetera	$40.75			
Treasurer's allowance for clerical hire	50.00			
		90.75		
Librarian's office		10.00		
Publication of Bulletin:				
Printing	$1,951.94			
Engraving	477.04			
Editor's allowance	250 00			
		2,678.98		
Refunded to J. C. Merriam		70.00		
			$4,016.25	
Balance on hand December 1, 1909, in bank			1,834.80	
				$5,851.05

Respectfully submitted,

WM. BULLOCK CLARK,
Treasurer.

BALTIMORE, MD., *December 1, 1909.*

EDITOR'S REPORT

To the Council of the Geological Society of America:

Owing to the condition of publication of volume 20, it is not possible for the Editor to furnish to the Council the usual data. All papers are in type and the proceedings of the Baltimore meeting are in the hands of the printer. A full statement will be included in the next Report of the Council.

J. STANLEY-BROWN,
Editor.

COLD SPRING HARBOR, LONG ISLAND,
December 20, 1909.

Register of the Boston-Cambridge Meeting, 1909

The following Fellows were in attendance at the meeting:

Frank Dawson Adams
Alfred Ernest Barlow
Joseph Barrell
George H. Barton
Florence Bascom
Ray Smith Bassler
Joshua W. Beede
Robert Bell
Charles P. Berkey
Samuel Walker Beyer
Eliot Blackwelder
John Adams Bownocker
Albert Perry Brigham
Reginald W. Brock
Charles Wilson Brown
Frank Carney
T. C. Chamberlin
Frederick G. Clapp
William Bullock Clark
John Mason Clarke
Herdman F. Cleland
Arthur P. Coleman
Whitman Cross
Henry P. Cushing
Reginald A. Daly
William M. Davis
Richard E. Dodge
John Alexander Dresser
Charles R. Eastman
Benjamin K. Emerson
Samuel F. Emmons
Herman L. Fairchild
August F. Foerste
Adam Capen Gill
Charles Newton Gould
Amadeus W. Grabau
Herbert E. Gregory
Frederic P. Gulliver
Arnold Hague
Christopher W. Hall
Thomas C. Hopkins
Edmund Otis Hovey
Horace C. Hovey
Ernest Howe
Ellsworth Huntington
John D. Irving
Robert T. Jackson
Thomas A. Jaggar, Jr.
Mark S. W. Jefferson
Albert Johannsen
Douglas Wilson Johnson
Arthur Keith
James F. Kemp
Henry B. Kümmel
Alfred C. Lane
William McInnes
Curtis F. Marbut
Benjamin L. Miller
Willet G. Miller
Ida Helen Ogilvie
Henry F. Osborn
Charles Palache
Horace B. Patton
Frederick B. Peck
Richard A. F. Penrose, Jr.
George H. Perkins
Albert Homer Purdue
Frederick Leslie Ransome
Harry Fielding Reid
William North Rice
Charles H. Richardson
George Burr Richardson
Heinrich Ries
Rudolph Ruedemann

Thomas Edmund Savage
Charles Schuchert
Will H. Sherzer
William John Sinclair
George Otis Smith
J. W. Spencer
Timothy William Stanton
Charles Kephart Swartz
Frank B. Taylor
Edward O. Ulrich
Frank Robertson Van Horn
Thomas Wayland Vaughan
Thomas L. Walker
Charles H. Warren
David White
Israel C. White
Henry S. Williams
Bailey Willis
Samuel W. Williston
Alfred W. G. Wilson
John E. Wolff
Jay B. Woodworth
Frederic E. Wright

Fellows-elect

Wallace Walter Atwood
Edson Sunderland Bastin
Edward Wilber Berry
Arthur Louis Day
Frank Walbridge De Wolf
James Walter Goldthwait
Baird Halberstadt
Frederic Brewster Loomis
Richard Swann Lull
George Rogers Mansfield
Lawrence Martin
William John Miller
Philip S. Smith

In addition, many visitors attended the sessions.

CONSTITUTION AND BY-LAWS

REFERENCES TO ADOPTION AND CHANGES

The provisional Constitution under which the Society was organized was approved August 15, 1888, and adopted December 27, 1888 (see Bulletin, volume 1, pages 7-8). These rules were elaborated and the revised Constitution and By-Laws were adopted December 27, 1889 (volume 1, pages 536, 571–578).

Several minor changes have been made in these rules, which are on record in the Bulletin as follows: Changes in the Constitution: December, 1894, volume 6, page 432; December, 1897, volume 9, page 400; December, 1909, volume 21, page 19. Changes in the By-Laws: December, 1891, volume 3, page 470; December, 1893, volume 5, pages 553-554; December, 1894, volume 6, page 432; December, 1903, volume 14, page 535; December, 1909, volume 21, page 19.

CONSTITUTION

Article I

NAME

This Society shall be known as The Geological Society of America.

Article II

OBJECT

The object of this Society shall be the promotion of the Science of Geology in North America.

Article III

MEMBERSHIP

The Society shall be composed of Fellows, Correspondents, and Patrons.

1. Fellows shall be persons who are engaged in geological work or in teaching geology.

Fellows admitted without election under the provisional Constitution shall be designated as Original Fellows on all lists or catalogues of the Society.

2. Correspondents shall be persons distinguished for their attainments in Geological Science and not resident in North America.

3. Patrons shall be persons who have bestowed important favors upon the Society.

4. Fellows alone shall be entitled to vote or hold office in the Society.

Article IV

OFFICERS

1. The Officers of the Society shall consist of a President, First and Second Vice-Presidents, a Secretary, a Treasurer, an Editor, and six Councilors.

These officers shall constitute an Executive Committee, which shall be called the Council.

2. The President shall discharge the usual duties of a presiding officer at all meetings of the Society and of the Council. He shall take cognizance of the acts of the Society and of its officers, and cause the provisions of the Constitution and By-Laws to be faithfully carried into effect.

3. The first Vice-President shall assume the duties of President in case of the absence or disability of the latter. The Second Vice-President shall assume the duties of President in case of the absence or disability of both the President and First Vice-President.

4. The Secretary shall keep the records of the proceedings of the Society, and a complete list of the Fellows, with the dates of their election and disconnection with the Society. He shall also be the secretary of the Council.

The Secretary shall coöperate with the President in attention to the ordinary affairs of the Society. He shall attend to the preparation, printing and mailing of circulars, blanks and notifications of elections and meetings. He shall superintend other printing ordered by the Society or by the President, and shall have charge of its distribution, under the direction of the Council.

The Secretary, unless other provision be made, shall also act as Editor of the publications of the Society, and as Librarian and Custodian of the property.

5. The Treasurer shall have the custody of all funds of the Society. He shall keep account of receipts and disbursements in detail, and this shall be audited as hereinafter provided.

6. The Editor shall supervise all matters connected with the publication of the transactions of the Society under the direction of the Council.

7. The Council is clothed with executive authority and with the legislative powers of the Society in the intervals between its meetings ; but no extraordinary act of the Council shall remain in force beyond the next following stated meeting without ratification by the Society. The Council shall have control of the publications of the Society, under provisions of the By-Laws and of resolutions from time to time adopted. They shall receive nominations for Fellows, and, on approval by them, shall submit such nominations to the Society for action. They shall have power to fill vacancies *ad interim* in any of the offices of the Society.

8. *Terms of office.*—The President and Vice-Presidents shall be elected annually, and shall not be eligible to re-election more than once until after an interval of three years after retiring from office.

The Secretary, Treasurer, and Editor shall be eligible to re-election without limitation.

The term of office of the Councilors shall be three years ; and these officers shall be so grouped that two shall be elected and two retire each year. Councilors retired shall not be re-eligible till after the expiration of a year.

Article V

VOTING AND ELECTIONS

1. All elections shall be by ballot. To elect a Fellow, Correspondent or Patron, or impose any special tax, shall require the assent of nine-tenths of all Fellows voting.

2. Voting by letter may be allowed.

3. *Election of Fellows.*—Nominations for fellowship may be made by two Fellows according to a form to be provided by the Council. One of these Fel-

lows must be personally acquainted with the nominee and his qualifications for membership. The Council will submit the nominations received by them, if approved, to a vote of the Society in the manner provided in the By-Laws. The result may be announced at any stated meeting; after which notice shall be sent out to Fellows elect.

4. *Election of officers.*—Nominations for office shall be made by the Council. The nominations shall be submitted to a vote of the Society in the same manner as nominations for fellowship. The results shall be announced at the Annual Meeting; and the officers thus elected shall enter upon duty at the adjournment of the meeting.

Article VI

MEETINGS

1. The Society shall hold at least one stated meeting a year, in the winter season. The date and place of the Winter Meeting shall be fixed by the Council, and announced each year within three months after the adjournment of the preceding Winter Meeting. The program of each meeting shall be determined by the Council, and announced beforehand, in its general features. The details of the daily sessions shall also be arranged by the Council.

2. The Winter Meeting shall be regarded as the Annual Meeting. At this, elections of officers shall be declared, and the officers elect shall enter upon duty at the adjournment of the meeting.

3. Special meetings may be called by the Council, and must be called upon the written request of twenty Fellows.

4. Stated meetings of the Council shall be held coincidently with the stated meetings of the Society. Special meetings may be called by the President at such times as he may deem necessary.

5. *Quorum.*—At meetings of the Society a majority of those registered in attendance shall constitute a quorum. Five shall constitute a quorum of the Council.

Article VII

PUBLICATION

The serial publications of the Society shall be under the immediate control of the Council.

Article VIII

SECTIONS

Any group of Fellows representing a particular branch of geology may, with consent of the Council, organize as a section of the Society with separate constitution and by-laws, provided that nothing in such constitution and by-laws conflict with the constitution and by-laws of the Geological Society of America, in letter or spirit, and provided that such constitution and by-laws and all amendments thereto shall have been approved by the Council.

Article IX

AMENDMENTS

1. This Constitution may be amended at any annual meeting by a three-fourths vote of all the Fellows, provided that the proposed amendment shall have been submitted in print to all Fellows at least three months previous to the meeting.

2. By-laws may be made or amended by a majority vote of the Fellows present and voting at any annual meeting, provided that printed notice of the proposed amendment or by-law shall have been given to all Fellows at least three months before the meeting.

BY–LAWS

Chapter I

OF MEMBERSHIP

1. No person shall be accepted as a Fellow unless he pay his initiation fee, and the dues for the year, within three months after notification of his election. The initiation fee shall be ten (10) dollars and the annual dues ten (10) dollars, the latter payable on or before the annual meeting in advance; but a single prepayment of one hundred (100) dollars shall be accepted as commutation for life.
2. The sums paid in commutation of dues shall be covered into the Publication Fund.
3. An arrearage in payment of annual dues shall deprive a Fellow of the privilege of taking part in the management of the Society and of receiving the publications of the Society. An arrearage continuing over two (2) years shall be construed as notification of withdrawal.
4. Any person eligible under Article III of the Constitution may be elected Patron upon the payment of one thousand (1,000) dollars to the Publication Fund of the Society.

Chapter II

OF OFFICIALS

1. The President shall countersign, if he approves, all duly authorized accounts and orders drawn on the Treasurer for the disbursement of money.
2. The Secretary, until otherwise ordered by the Society, shall perform the duties of Editor, Librarian, and Custodian of the property of the Society.
3. The Society may elect an Assistant Secretary.
4. The Treasurer shall give bonds, with two good sureties approved by the Council, in the sum of five thousand dollars, for the faithful and honest performance of his duties and the safe-keeping of the funds of the Society. He may deposit the funds in bank at his discretion, but shall not invest them without authority of the Council. His accounts shall be balanced as on the thirtieth day of November of each year.
5. In the selection of Councilors the various sections of North America shall be represented as far as practicable.
6. The minutes of the proceedings of the Council shall be subject to call by the Society.
7. The Council may transact its business by correspondence during the intervals between its stated meetings; but affirmative action by a majority of the Council shall be necessary in order to make action by correspondence valid.

Chapter III

OF ELECTION OF MEMBERS

1. Nominations for fellowship may be proposed at any time on blanks to be supplied by the Secretary.

2. The *form* for the nomination of Fellows shall be as follows:

In accordance with his desire, we respectfully nominate for Fellow of the Geological Society of America:

Full name; degrees; address; occupation; branch of Geology now engaged in, work already done and publications made.

(Signed by at least two Fellows.)

The form when filled is to be transmitted to the Secretary.

3. The Secretary will bring all nominations before the Council, and the Council will signify its approval or disapproval of each.

4. At least a month before one of the stated meetings of the Society the Secretary will mail a printed list of all approved nominees to each Fellow, accompanied by such information as may be necessary for intelligent voting; but an informal list of the candidates shall be sent to each Fellow at least two weeks prior to distribution of the ballots.

5. The Fellows receiving the list will signify their approval or disapproval of each nominee, and return the lists to the Secretary.

6. At the next stated meeting of the Council the Secretary will present the lists and the Council will canvass the returns.

7. The Council, by unanimous vote of the members in attendance, may still exercise the power of rejection of any nominee whom new information shows to be unsuitable for fellowship.

8. At the next stated meeting of the Society the Council shall declare the results.

9. Correspondents and Patrons shall be nominated by the Council, and shall be elected in the same manner as Fellows.

Chapter IV

OF ELECTION OF OFFICERS

1. The Council shall prepare a list of nominations for the several offices, which list will constitute the regular ticket. The ticket must be approved by a majority of the entire Council. The nominee for President shall not be a member of the Council. One of the nominees for vice-president shall be the nominee for the presidency of the Paleontological Society which has been organized as a section under Article VIII of the Constitution.

2. The list shall be mailed to the Fellows, for their information, at least nine months before the Annual Meeting. Any five Fellows may forward to the Secretary other nominations for any or all offices. All such nominations reaching the Secretary at least 40 days before the Annual Meeting shall be printed, together with the names of the nominators, as special tickets. The regular and special tickets shall then be mailed to the Fellows at least 25 days before the Annual Meeting.

3. The Fellows will send their ballots to the Secretary in double envelopes, the outer envelope bearing the voter's name. At the Winter Meeting of the

Council, the Secretary will bring the returns of ballots before the Council for canvass, and during the Winter Meeting of the Society the Council shall declare the result.

4. In case a majority of all the ballots shall not have been cast for any candidate for any office, the Society shall by ballot at such Winter Meeting proceed to make an election for such office from the two candidates having the highest number of votes.

Chapter V

OF FINANCIAL METHODS

1. No pecuniary obligation shall be contracted without express sanction of the Society or the Council. But it is to be understood that all ordinary, incidental, and running expenses have the permanent sanction of the Society, without special action.

2. The creditor of the Society must present to the Treasurer a fully itemized bill, certified by the official ordering it, and approved by the President. The Treasurer shall then pay the amount out of any funds not otherwise appropriated, and the receipted bill shall be held as his voucher.

3. At each annual meeting, the President shall call upon the Society to choose two Fellows, not members of the Council, to whom shall be referred the books of the Treasurer, duly posted and balanced to the close of November thirtieth, as specified in the By-Laws, Chapter II, clause 4. The Auditors shall examine the accounts and vouchers of the Treasurer, and any member or members of the Council may be present during the examination. The report of the Auditors shall be rendered to the Society before the adjournment of the meeting, and the Society shall take appropriate action.

Chapter VI

OF PUBLICATIONS

1. The publications are in charge of the Council and under its control.

2. One copy of each publication shall be sent to each Fellow, Correspondent, and Patron, and each author shall receive thirty (30) copies of his memoir.

Chapter VII

OF THE PUBLICATION FUND

1. The Publication Fund shall consist of donations made in aid of publication, and of the sums paid in commutation of dues, according to the By-Laws, Chapter I, clause 2.

2. Donors to this fund, not Fellows of the Society, in the sum of two hundred dollars, shall be entitled, without charge, to the publications subsequently appearing.

Chapter VIII

OF ORDER OF BUSINESS

1. The Order of Business at Winter Meetings shall be as follows:

   (1) Call to order by the presiding officer.

   (2) Introductory ceremonies.

(3) Report of the Council (including report of the officers).
(4) Appointment of the Auditing Committee.
(5) Declaration of the vote for officers, and election by the meeting in case of failure to elect by the Society through transmitted ballots.
(6) Declaration of the vote for Fellows.
(7) Deferred business.
(8) New business.
(9) Announcements.
(10) Necrology.
(11) Reading of scientific papers.

2. At an adjourned session the order shall be resumed at the place reached on the previous adjournment, but new business will be in order before the reading of scientific papers.

3. At the Summer Meeting the items of business under numbers (3), (4), (5), (10) shall be omitted.

4. At any Special Meeting the order of business shall be numbers (1), (2), (3), (9), followed by the special business for which the meeting was called.

PUBLICATION RULES OF THE GEOLOGICAL SOCIETY OF AMERICA

(Adopted by the Council April 21, 1891; Revised April 30, 1894, May, 1904, and February 5, 1910)

General Provisions

Section 1. The Council shall annually appoint from their own number a Publication Committee, consisting of the Secretary, the Treasurer, the Editor, and two others, whose duties shall be to determine the disposition of matter offered for publication, except as provided in section 12; to determine the expediency, in view of the financial condition of the Society, of publishing any matter accepted on its merits; to exercise general oversight of the matter and manner of publication; to determine the share of the cost of publication (including illustrations) to be borne by the author when it becomes necessary to divide cost between the Society and the author; to adjudicate any questions relating to publication that may be raised from time to time by the Editor or by the Fellows of the Society; and in general to act for the Council in all matters pertaining to publication. (Cons., Art. IV, 7; Art. VII; By-Laws, chap. VI.)

2. The duties of the Editor are to receive material offered for publication; to examine and submit it, with estimates of cost, to the Publication Committee; to publish all material accepted by the Council or Publication Committee; to revise proofs in connection with authors; to prepare lists of contents and general indexes; to audit bills for printing and illustrating; and to perform all other duties connected with publication not assigned to other officers. (Cons., Art. IV, 6; Rules, Sec. 16.)

3. The duties of the Secretary include the preparation of a record of the proceedings of each meeting of the Society in form for publication, and the custody, distribution, sale, exchange or other authorized disposition of the publications. (Cons., Art. IV, 4; By-Laws, chap. II, 2.)

4. Special committees may be appointed by the Council or the Publication Committee to examine and report on any matter offered for publication. (Rules, Sec. 11.)

The Bulletin

Title and General Character

5. The Society shall publish a serial record of its work entitled "Bulletin of the Geological Society of America."

6. The Bulletin shall be published in quarterly parts, consecutively paged for each volume. The parts shall be suitably designated and each shall bear a title setting forth the contents and authorship, the seal and imprint of the Society and the date of publication.

7. The closing quarterly part of each volume shall contain an index, paged consecutively with the body of the volume; and it shall be accompanied by a volume title-page and lists of contents and illustrations, together with lists of

the publications of the Society and such other matter as the Publication Committee may deem necessary, all arranged under Roman pagination.

MATTER OF THE BULLETIN

8. The matter published in the Bulletin shall comprise (1) communications presented at meetings by title or otherwise; (2) communications or memoirs not presented before the Society; (3) abstracts of papers read before the Society, prepared or revised for publication by authors; (4) reports of discussions held before the Society, prepared or revised for publication by authors; (5) proceedings of the meetings of the Society prepared by the Secretary; (6) plates, maps, and other illustrations necessary for the proper understanding of communications; (7) lists of Officers and Fellows, Constitution, By-Laws, resolutions of permanent character, rules relating to procedure, to publication, and to other matters, etcetera, and (8) indexes, title-pages, and lists of contents for each volume.

9. Abstracts, reports of discussion, or other matter purporting to emanate from any author shall not be published unless prepared or revised by the author.

10. Manuscript designed for publication in the Bulletin must be complete as to copy for text and illustration, except by special arrangement between the author and the Council or Publication Committee; it must be perfectly legible (preferably typewritten) and preceded by a table of contents (section 20). The cost of necessary revision of copy or reconstruction of illustrations shall be assessed on the author.

11. The Editor shall examine matter designated for publication, and shall prepare an itemized estimate of the cost of publication and convey the whole to the Publication Committee. The Publication Committee shall then scrutinize the communication with reference, first, to relevancy; second, to scientific value; third, to literary character, and, fourth, to cost of publication, including revision. For advice with reference to the relevancy, scientific value, and literary character of any communication the Publication Committee may refer it to a special committee of their own number or of the Society at large or may call to their aid from outside one or more experts. Questions of disagreement between the Editor and authors shall be referred to the Publication Committee. and appeal may be taken to the Council.

12. Communications from non-fellows shall be published only by specific authority from the Council.

13. Communications from Fellows not presented at regular meetings of the Society shall be published only upon unanimous vote of the Publication Committee, except by specific authority from the Council.

14. Matter offered for publication becomes thereby the property of the Society, and shall not be published elsewhere prior to publication in the Bulletin, except by consent of the Publication Committee.

DETAILS OF THE BULLETIN

15. The matter of each memoir shall be classified by subjects, and the classification suitably indicated by subtitles; and a list of contents shall be arranged; and such memoir may, at the option of the Publication Committee, contain an alphabetical index, provided the author prepare and pay for it.

16. Proofs of text and illustrations shall be submitted to authors whenever practicable; but printing shall not be delayed by reason of absence or incapacity of authors more than one week beyond the time required for transmission by mail. Complete proofs of the proceedings of meetings shall be sent to the Secretary, and proofs of papers and abstracts contained therein and exceeding one-half page in length shall be sent also to authors.

17. The cost of proof corrections in excess of five per cent on the cost of printing may be charged to authors.

18. Unless the author of a memoir objects thereto, the discussion upon his communication shall be printed at the end thereof, with a suitable reference in the list of contents. In case the author objects to this arrangement, the discussion shall be printed in the closing number of the volume.

19. The author of each memoir occupying eight pages or more of text in the body of the Bulletin shall receive 30 "separates" without charge, and may order through the Editor any edition of exactly similar separates at an advance of ten per cent. on the cost of paper, presswork and binding; and no author's separates of such memoirs shall be issued except in this regular form.

20. Authors of papers, abstracts, or discussions less than eight printed pages in length may order, through the Editor, at an advance of ten per cent. on the cost of paper, presswork, binding and necessary composition, any number of extra copies, provided they bear the original pagination and a printed reference to the serial and volume from which they are extracted.

21. The Editor shall keep a record of all publications issued wholly or in part under the auspices of the Society, whether the same be author's editions of memoirs, author's extracts from proceedings, or any other matter printed from type originally composed for the Bulletin.

DIRECTIONS TO PRINTER

22. Each memoir of the Bulletin shall begin, under its proper title, on an odd-numbered page bearing at its head the title of the serial, the volume number, the part number, the limiting pages, the plates, and the date of publication, together with a list of contents. Each memoir shall be accompanied by the illustrations pertaining to it, the plates numbered consecutively for the volume.

23. The author's separates of each memoir shall be enclosed in a cover bearing at the head of its title-page the title of the serial, the volume number, the limiting pages, and the numbers of the contained plates; in its upper-central part a title indicating the contents and authorship; in its lower-central part the seal of the Society; and at the bottom the imprint of the Society. (See also Sections 19 and 20.)

24. The bottom of each signature and each initial page will bear a signature mark giving an abbreviated title of the serial, the volume, and the year; and every page (except volume title-page) shall be numbered, the initial and subtitle pages in parentheses at bottom.

25. The page-head titles shall be: on even-numbered pages, name of author and catch title of paper; on odd-numbered pages, catch title to contents of page.

26. The date of publication of each brochure shall be the day upon which the last form is locked and put on the press.

27. The type used in printing the Bulletin shall be as follows: For memoirs, body, long primer, 6-to-pica leads; extracts, brevier, 8-to-pica leads; footnotes, nonpareil, set solid; titles, long primer caps, with small caps for author's name; subtitles, long primer caps, small caps, italic, etcetera, as far as practicable; for designation of cuts, nonpareil caps and italics, and for legends, nonpareil, Roman, set solid; for lists of contents of brochures, brevier, 6-to-pica leads, a new line to an entry, running indentation; for volumes, the same, except 4-to-pica leads and names of authors in small caps; for indexes, nonpareil, set solid, double column, leaders, catch words in small caps, with spaces between initial letters. For serial titles, on initial pages, brevier block caps, with corresponding small caps for volume designation, etcetera; on covers, the same, except for page heads long primer caps; for serial designation, long primer; for brochure designation, pica caps; special title and author's name, etcetera, long primer and brevier caps; no frame on cover. No change in type shall be made to adjust matter to pages.

28. Volumes, plates, and cuts in text shall be numbered in Arabic; Roman numeration shall be used only in signature marks, and in paging the lists of contents, etcetera, arranged for binding at the beginning of the volume.

29. Imprimatur of Editor, on volume title-page; imprimatur of Council and Publication Committee, on obverse of volume title-page; imprimatur of Secretary, on initial pages and covers of brochures of proceedings. Printer's card, in fine type on obverse of title-page.

30. The paper shall be for body of volume, 70-pound toned paper, folding to 16 x 25 centimeters; for plates, good quality plate paper, smooth-surfaced, white, cut to 6½ x 10 inches for single plates; for covers smooth-surfaced, fine quality 70-pound light-buff manila paper.

31. The sheets of the brochures shall be stitched with thread; single page plates shall be stitched with the sheets of the brochure; folding plates may be either gummed or stitched (mounted on stubs if necessary); covers shall be gummed.

EDITION, DISTRIBUTION, AND PRICE

32. The regular edition shall be 545 copies in the regular quarterly form and 40 copies separately in covers of each memoir occupying eight pages or more of text. Each author shall receive 30 copies of his memoir gratis. If two or more authors contribute to a memoir brochure of eight pages or more in length, the edition shall be enlarged so as to give each author 30 copies. (By-Laws, chap. VI, 2.)

33. The undistributed residue of separates shall be held for sale.

34. The Bulletin shall be sent free to Fellows of the Society not in arrears for dues more than one year, and also to exchanging institutions. (By-Laws, chap. I, 3.)

35. The price of the Bulletin shall be as follows: To Fellows, libraries, and institutions, and to individuals not residing in North America, $7.50 per volume; to individuals residing in North America and who are not Fellows, $10. The price of each brochure shall be a multiple of five cents, and shall be, to Fellows, an advance on cost of about 100 per cent. and to the public an advance on cost of about 200 per cent. The prices of the separate brochures may be found in the front of each volume.

OFFICERS, CORRESPONDENTS, AND FELLOWS OF THE GEOLOGICAL SOCIETY OF AMERICA

OFFICERS FOR 1910

President:

Arnold Hague, Washington, D. C.

Vice-Presidents:

Charles Schuchert, New Haven, Conn.
A. P. Low, Ottawa, Ont.

Secretary:

Edmund Otis Hovey, American Museum of Natural History, New York, N. Y.

Treasurer:

Wm. Bullock Clark, Baltimore, Maryland

Editor:

J. Stanley-Brown, Cold Spring Harbor, Long Island, N. Y.

Librarian:

H. P. Cushing, Cleveland, Ohio

Councilors:

(Term expires 1910)

H. P. Cushing, Cleveland, Ohio
H. B. Patton, Golden, Colorado

(Term expires 1911)

Geo. Otis Smith, Washington, D. C.
Henry S. Washington, Locust, New Jersey

(Term expires 1912)

J. B. Woodworth, Cambridge, Mass.
C. S. Prosser, Columbus, Ohio.

MEMBERS, DECEMBER 31, 1909

CORRESPONDENTS

Charles Barrois, D. ès Sc., D. Sc., Lille, France. Professor of Geology at the University. December, 1909.

W. C. Brögger, Sc. D., LL. D., Christiania, Norway. Professor of Geology and Mineralogy at the Royal University. December, 1909.

Sir Archibald Geikie, D. C. L., Sc. D., LL. D., Hasslemere, England. President of the Royal Society, late Director General of the Geological Society of the United Kingdom. December, 1909.

Albrecht Heim, D. Sc., Zürich, Switzerland. President of the Swiss Geological Commission and Professor of Geology at the University. December, 1909.

Emanuel Kayser, Ph. D., Marburg, Germany. Professor of Geology at the University. December, 1909.

Eduard Suess, Ph. D., Vienna, Austria. Formerly Professor of Geology at the Imperial Royal University, President of the Imperial Academy of Sciences. December, 1909.

Ferdinand Zirkel, D. Sc., Ph. D., Königstrasse 27, Bonn, Germany. Geheimer Rath, Professor (retired) of Mineralogy and Geology at the University of Leipzig. December, 1909.

FELLOWS

*Indicates Original Fellow (see article III of Constitution)

Cleveland Abbe, Jr., Ph. D., U. S. Weather Bureau, Washington, D. C. August, 1899.

Frank Dawson Adams, Ph. D., Montreal, Canada; Professor of Geology in McGill University. December, 1889.

George I. Adams, Sc. D., Bureau of Mines, Manila, P. I. December, 1902.

José Guadalupe Aguilera, Ph. D., City of Mexico, Mexico; Director del Instituto Geologico de Mexico. August, 1896.

Truman H. Aldrich, M. E., 1739 P St. N. W., Washington, D. C. May, 1889.

Henry M. Ami, A. M., Ottawa, Canada; Assistant Paleontologist on Geological and Natural History Survey of Canada. December, 1889.

Frank M. Anderson, B. A., M. S., 2604 Ætna Street, Berkeley, Cal. California State Mining Bureau. June, 1902.

Philip Argall, 728 Majestic Building, Denver, Colo. August, 1896.

Ralph Arnold, Ph. D., 726 H. W. Hellman Bldg., Los Angeles, Cal. December, 1904.

George Hall Ashley, M. E., Ph. D., Washington, D. C.; U. S. Geological Survey. August, 1895.

Rufus Mather Bagg, Jr., Ph. D., 603 W. Green St., Urbana, Ill.; Instructor in Geology in University of Illinois. December, 1896.

Harry Foster Bain, M. S., 667 Howard St., San Francisco, Cal. December, 1895.

S. Prentiss Baldwin, 736 Prospect St., Cleveland, Ohio. August, 1895.

Sydney H. Ball, A. B., 71 Broadway, New York City. December, 1905.

Erwin Hinckley Barbour, Ph. D., Lincoln, Neb.; Professor of Geology, University of Nebraska, and Acting State Geologist. December, 1896.

Alfred Ernest Barlow, B. A., M. A., D. Sc., 24 Durochen St., Montreal, Canada. December, 1906.

Joseph Barrell, Ph. D., New Haven, Conn.; Professor of Structural Geology, Yale University. December, 1902.

George H. Barton, B. S., Boston, Mass.; Curator, Boston Society of Natural History. August, 1890.

Florence Bascom, Ph. D., Bryn Mawr, Pa.; Professor of Geology, Bryn Mawr College. August, 1894.

Ray Smith Bassler, B. A., M. S., Ph. D., Washington, D. C.; U. S. National Museum. December, 1906.

William S. Bayley, Ph. D., Urbana, Ill.; Assistant Professor of Geology, University of Illinois. December, 1888.

*George F. Becker, Ph. D., Washington, D. C.; U. S. Geological Survey.

Joshua W. Beede, Ph. D., Bloomington, Ind.; Instructor in Geology, Indiana University. December, 1902.

Robert Bell, I. S. O., Sc. D., M. D., LL. D., F. R. S., Ottawa, Canada; Chief Geologist, Geological Survey, Department of Mines. May, 1889.

Charles P. Berkey, Ph. D., New York City; Instructor in Geology, Columbia University. August, 1901.

Samuel Walker Beyer, Ph. D., Ames, Iowa; Assistant Professor in Geology, Iowa Agricultural College. December, 1896.

Arthur B. Bibbins, Ph. B., Baltimore, Md.; Instructor in Geology, Woman's College. December, 1903.

Albert S. Bickmore, Ph. D., 863 Seventh Ave., New York City; Curator Emeritus, Department of Public Instruction, American Museum of Natural History. December, 1889.

Irving P. Bishop, 109 Norwood Ave., Buffalo, N. Y.; Professor of Natural Science, State Normal and Training School. December, 1899.

Elliot Blackwelder, A. B., Madison, Wis.; Assistant Professor of Geology in University of Wisconsin. December, 1908.

William Phipps Blake, Ph. B., Tucson, Arizona; Director School of Mines, Arizona, and Territorial Geologist. December, 1908.

John M. Boutwell, M. S., Washington, D. C.; Assistant Geologist, U. S. Geological Survey. December, 1905.

John Adams Bownocker, D. Sc., Columbus, Ohio; Professor of Inorganic Geology, Ohio State University. December, 1904.

*John C. Branner, Ph. D., Stanford University, Cal.; Professor of Geology in Leland Stanford, Jr., University.

Albert Perry Brigham, A. B., A. M., Hamilton, N. Y.; Professor of Geology and Natural History, Colgate University. December, 1893.

Reginald W. Brock, M. A., Ottawa, Canada; Director, Geological Survey, Department of Mines. December, 1904.

Alfred Hulse Brooks, B. S., Washington, D. C.; Assistant Geologist, U. S. Geological Survey. August, 1899.

Amos P. Brown, Ph. D., Philadelphia, Pa.; Professor of Mineralogy and Geology, University of Pennsylvania. December, 1905.

Charles Wilson Brown, Ph. D., A. M., Providence, R. I.; Assistant Professor and Head of the Department of Geology in Brown University. December, 1908.

Ernest Robertson Buckley, Ph. D., Rolla, Mo. June, 1902.

*Samuel Calvin, Ph. D., LL. D., Iowa City, Iowa; State Geologist; Professor of Geology in the State University of Iowa.

Henry Donald Campbell, Ph. D., Lexington, Va.; Professor of Geology and Biology in Washington and Lee University. May, 1889.

Marius R. Campbell, Washington, D. C.; U. S. Geological Survey. August, 1892.

Frank Carney, A. B., Granville, Ohio; Professor of Geology in Denison University. December, 1908.

Franklin R. Carpenter, Ph. D., 1420 Josephine St., Denver, Colo. May, 1889.

Ermine C. Case, Ph. D., Ann Arbor, Mich.; Department of Geology, University of Michigan. December, 1901.

*T. C. Chamberlin, LL. D., Chicago, Ill.; Head Professor of Geology, University of Chicago.

Clarence Raymond Claghorn, B. S., M. E., Tacoma, Wash. August, 1891.

Frederick G. Clapp, S. B., 610 Fitzsimmons Bldg., Pittsburgh, Pa. Dec., 1905.

*William Bullock Clark, Ph. D., Baltimore, Md.; Professor of Geology in Johns Hopkins University; State Geologist.

John Mason Clarke, A. M., Ph. D., Albany, N. Y.; State Paleontologist. December, 1897.

Herdman F. Cleland, Ph. D., Williamstown, Mass.; Professor of Geology, Williams College. December, 1905.

J. Morgan Clements, Ph. D., Room 1707, 42 Broadway, New York City. December, 1894.

Collier Cobb, A. B., A. M., Chapel Hill, N. C.; Professor of Geology in University of North Carolina. December, 1894.

Arthur P. Coleman, Ph. D., Toronto, Canada; Professor of Geology, Toronto University, and Geologist of Bureau of Mines of Ontario. December, 1896.

George L. Collie, Ph. D., Beloit, Wis.; Professor of Geology in Beloit College. December, 1897.

Arthur J. Collier, A. M., S. B., Washington, D. C.; Assistant Geologist, U. S. Geological Survey. June, 1902.

*Theodore B. Comstock, Sc. D., Los Angeles, Cal.

Eugene Coste, B. ès-Sc., E. M., Toronto, Canada. December, 1906.

*Francis W. Cragin, Ph. D., Colorado Springs, Colo.; Professor of Geology in Colorado College.

Alja Robinson Crook, Ph. D., Springfield, Ill.; State Museum of Natural History. December, 1898.

*William O. Crosby, B. S., Boston, Mass.; Professor of Geology in Massachusetts Institute of Technology.

Whitman Cross, Ph. D., Washington, D. C.; U. S. Geological Survey. May, 1889.

Garry E. Culver, A. M., 1104 Wisconsin St., Stevens Point, Wis. December, 1891.

Edgar R. Cumings, Ph. D., Bloomington, Ind.; Professor of Geology, Indiana University. August, 1901.

*Henry P. Cushing, M. S., Ph. D., Adelbert College, Cleveland, Ohio; Professor of Geology, Western Reserve University.

Reginald A. Daly, Ph. D., Boston, Mass.; Massachusetts Institute of Technology. December, 1905.

Edward Salisbury Dana, A. B., A. M., Ph. D., 24 Hillhouse Ave., New Haven, Conn.; Professor of Physics and Curator of Mineralogical Collection in Yale University. December, 1908.

*Nelson H. Darton, Washington, D. C.; U. S. Geological Survey.

*William M. Davis, S. B., M. E., Cambridge, Mass.; Sturgis-Hooper Professor of Geology in Harvard University.

David T. Day, Ph. D., Washington, D. C.; U. S. Geological Survey. August, 1891.

Orville A. Derby, M. S., No. 80 Rua Visconde do Rio Branco, Sao Paulo, Brazil. December, 1890.

*Joseph S. Diller, B. S., Washington, D. C.; U. S. Geological Survey.

Edward V. d'Invilliers, E. M., 506 Walnut St., Philadelphia, Pa. December, 1888.

Richard E. Dodge, A. M., New York City; Professor of Geography in Teachers' College. August, 1897.

Noah Fields Drake, Ph. D., Tientsin, China; Professor of Geology in Imperial Tientsin University. December, 1898.

John Alexander Dresser, B. A., M. A., Ottawa, Ontario, Canada. Geologist, Geological Survey of Canada. December, 1906.

Charles R. Dryer, M. A., M. D., Terre Haute, Ind.; Professor of Geography, Indiana State Normal School. August, 1897.

*Edwin T. Dumble, 1306 Main St., Houston, Texas.

Clarence Edward Dutton, A. B., Englewood, N. J.; Major, U. S. A. (retired). December, 1907.

Arthur S. Eakle, Ph. D., Berkeley, Cal.; Instructor in Mineralogy, University of California. December, 1899.

Charles R. Eastman, A. M., Ph. D., Cambridge, Mass.; In Charge of Vertebrate Paleontology, Museum of Comparative Zoology, Harvard University. December, 1895.

Edwin C. Eckel, B. S., C. E., Munsey Building, Washington, D. C. December, 1905.

Arthur H. Elftman, Ph. D., P. O. Box 601, Tonopah, Nevada. Dec., 1898.

*Benjamin K. Emerson, Ph. D., Amherst, Mass.; Professor in Amherst College.

*Samuel F. Emmons, A. M., E. M., Washington, D. C.; U. S. Geological Survey.

John Eyerman, F. Z. S., Oakhurst, Easton, Pa. August, 1891.

Harold W. Fairbanks, B. S., Berkeley, Cal.; Geologist State Mining Bureau. August, 1892.

*Herman L. Fairchild, B. S., Rochester, N. Y.; Professor of Geology in University of Rochester.

Oliver C. Farrington, Ph. D., Chicago, Ill.; Curator of Geology, Field Museum of Natural History. December, 1895.

Nevin M. Fenneman, Ph. D., Cincinnati, Ohio; Professor of Geology, University of Cincinnati. December, 1904.

Cassius Asa Fisher, A. B., A. M., 1832 Baltimore St. N. W., Washington, D. C.; U. S. Geological Survey. December, 1908.

August F. Foerste, Ph. D., 417 Grand Ave., Dayton, Ohio; Teacher of Sciences, Steele High School. December, 1899.

William M. Fontaine, A. M., Charlottesville, Va.; Professor of Natural History and Geology in University of Virginia. December, 1888.

Myron Leslie Fuller, S. B., 104 Belmont Ave., Brockton, Mass. December, 1898.

Henry Stewart Gane, Ph. D., Santa Barbara, Cal. December, 1896.

Henry Gannett, S. B., A. Met. B., Washington, D. C.; U. S. Geological Survey. December, 1891.

Russell D. George, A. B., A. M., Boulder, Colo.; Professor of Geology, University of Colorado. December, 1906.

*Grove K. Gilbert, A. M., LL. D., Washington, D. C.; U. S. Geological Survey.

Adam Capen Gill, Ph. D., Ithaca, N. Y.; Assistant Professor of Mineralogy and Petrography in Cornell University. December, 1888.

L. C. Glenn, Ph. D., Nashville, Tenn.; Professor of Geology in Vanderbilt University. June, 1900.

Charles H. Gordon, Ph. D., Knoxville, Tenn.; Professor of Geology and Mineralogy in the University of Tennessee. August, 1893.

Charles Newton Gould, A. M., Norman, Okla.; Professor of Geology, University of Oklahoma. December, 1904.

Amadeus W. Grabau, S. M., S. D., New York City; Professor of Paleontology, Columbia University. December, 1898.

Ulysses Sherman Grant, Ph. D., Evanston, Ill.; Professor of Geology, Northwestern University. December, 1890.

Herbert E. Gregory, Ph. D., New Haven, Conn.; Silliman Professor of Geology, Yale University. August, 1901.

George P. Grimsley, Ph. D., Martinsburg, W. Va.; Assistant State Geologist, Geological Survey of West Virginia. August, 1895.

Leon S. Griswold, A. B., Rolla, Missouri. August, 1902.

Frederic P. Gulliver, Ph. D., Norwichtown, Conn. August, 1895.

Arnold Hague, Ph. B., Washington, D. C.; U. S. Geological Survey. May, 1889.

*Christopher W. Hall, A. M., 803 University Ave., Minneapolis, Minn.; Professor of Geology and Mineralogy in University of Minnesota.

Gilbert D. Harris, Ph. B., Ithaca, N. Y.; Assistant Professor of Paleontology and Stratigraphic Geology, Cornell University. December, 1903.

John Burchmore Harrison, M. A., F. I. C., F. G. S., Georgetown, British Guiana; Government Geologist. June, 1902.

John B. Hastings, M. E., 1480 High St., Denver, Colo. May, 1889.

*Erasmus Haworth, Ph. D., Lawrence, Kans.; Professor of Geology, University of Kansas.

C. Willard Hayes, Ph. D., Washington, D. C.; U. S. Geological Survey. May, 1889.

Richard R. Hice, B. S., Beaver, Pa. December, 1903.

*Eugene W. Hilgard, Ph. D., LL. D., 2728 Bancroft Way, Berkeley, Cal.; Professor of Agriculture in University of California.

Frank A. Hill, Roanoke, Va. May, 1889.

*Robert T. Hill, B. S., 25 Broad St., New York City.

Richard C. Hills, Denver, Colo. August, 1894.

*Charles H. Hitchcock, Ph. D., LL. D., Honolulu, Hawaiian Islands; Professor Emeritus of Geology in Dartmouth College, Hanover, N. H.

William Herbert Hobbs, Ph. D., Ann Arbor, Mich.; Professor of Geology, University of Michigan; Assistant Geologist, U. S. Geological Survey. August, 1891.

*Levi Holbrook, A. M., P. O. Box 536, New York City.

Arthur Hollick, Ph. D., Bronx Park, New York City; Assistant Curator, Department of Fossil Botany, New York Botanical Garden. August, 1893.

*Joseph A. Holmes, Washington, D. C.; in charge of investigation of fuels and structural materials, U. S. Geological Survey.

Thomas C. Hopkins, Ph. D., Syracuse, N. Y.; Professor of Geology, Syracuse University. December, 1894.

*Edmund Otis Hovey, Ph. D., New York City; Curator of Geology and Invertebrate Paleontology, American Museum of Natural History.

*Horace C. Hovey, D. D., Newburyport, Mass.

Ernest Howe, Ph. D., 75 Kay St., Newport, R. I.; Assistant Geologist, U. S. Geological Survey. December, 1903.

*Edwin E. Howell, A. M., 612 Seventeenth St. N. W., Washington, D. C.

Lucius L. Hubbard, Ph. D., LL. D., Houghton, Mich. December, 1894.

Ellsworth Huntington, A. B., A. M., New Haven, Conn.; Instructor in Geography, Yale University. December, 1906.

Joseph P. Iddings, Ph. B., Chicago, Ill.; Professor of Petrographic Geology, University of Chicago. May, 1889.

John D. Irving, Ph. D., New Haven, Conn.; Professor of Economic Geology, Yale University. December, 1905.

A. Wendell Jackson, Ph. B., 432 Saint Nicholas Ave., New York City. December, 1888.

Robert T. Jackson, S. D., 9 Fayerweather St., Cambridge, Mass.; Assistant Professor in Paleontology in Harvard University. August, 1894.

Thomas M. Jackson, C. E., S. D., Clarksburg, W. Va. May, 1889.

Thomas Augustus Jaggar, Jr., A. B., A. M., Ph. D., Boston, Mass.; Professor of Geology, Massachusetts Institute of Technology. December, 1906.

Mark S. W. Jefferson, A. M., Ypsilanti, Mich.; Professor of Geography, Michigan State Normal College. December, 1904.

Albert Johannsen, B. S., Ph. D., Chicago, Ill.; Department of Geology, University of Chicago. December, 1908.

Douglas Wilson Johnson, B. S., Ph. D., Cambridge, Mass.; Assistant Professor of Physiography, Harvard University. December, 1906.

Alexis A. Julien, Ph. D., New York City; Curator (emeritus) in Geology in Columbia University. May, 1889.

George Frederick Kay, M. A., Iowa City, Iowa; Professor of Mineralogy, Petrography, and Economic Geology in State University of Iowa. December, 1908.

Arthur Keith, A. M., Washington, D. C.; U. S. Geological Survey. May, 1889.

*James F. Kemp, A. B., E. M., New York City; Professor of Geology in Columbia University.

Charles Rollin Keyes, Ph. D., 944 Fifth St., Des Moines, Iowa. August, 1890.

Edward M. Kindle, Ph. D., Washington, D. C.; Assistant Geologist, U. S. Geological Survey. December, 1905.

Frank H. Knowlton, M. S., National Museum, Washington, D. C.; Assistant Paleontologist, U. S. Geological Survey. May, 1889.

Edward Henry Kraus, Ph. D., Ann Arbor, Mich.; Junior Professor of Mineralogy, University of Michigan. June, 1902.

Henry B. Kümmel, Ph. D., Trenton, N. J.; State Geologist. December, 1895.

*George F. Kunz, A. M. (Hon.), Ph. D. (Hon.), care of Tiffany & Co., Fifth Ave., at 37th St., New York City.

George Edgar Ladd, Ph. D., Rolla, Mo.; Director, School of Mines. August, 1891.

J. C. K. Laflamme, M. A., D. D., Quebec, Canada; Professor of Mineralogy and Geology in Laval University, Quebec. August, 1890.

Henry Landes, A. B., A. M., University Station, Seattle, Wash.; Professor of Geology in University of Washington. December, 1908.

Alfred C. Lane, Ph. D., Tufts College, Mass.; Pearson Professor of Geology in Tufts College. December, 1889.

Andrew C. Lawson, Ph. D., Berkeley, Cal.; Professor of Geology and Mineralogy in the University of California. May, 1889.

Willis Thomas Lee, M. S., Washington, D. C.; Assistant Geologist, U. S. Geological Survey. December, 1903.

Charles K. Leith, Ph. D., Madison, Wis.; Professor of Geology, University of Wisconsin; Assistant Geologist, U. S. Geological Survey. December, 1902.

Arthur G. Leonard, Ph. D., Grand Forks, N. Dak.; Professor of Geology and State Geologist, State University of North Dakota. December, 1901.

Frank Leverett, B. S., Ann Arbor, Mich.; Geologist, U. S. Geological Survey. August, 1890.

Joseph Volney Lewis, B. E., S. B., New Brunswick, N. J.; Professor of Geology, Rutgers College. December, 1906.

William Libbey, Sc. D., Princeton, N. J.; Professor of Physical Geography in Princeton University. August, 1899.

Waldemar Lindgren, M. E., Washington, D. C.; U. S. Geological Survey. August, 1890.

George Davis Louderback, Ph. D., Berkeley, Cal.; Associate Professor of Geology, University of California. June, 1902.

Robert H. Loughridge, Ph. D., Berkeley, Cal.; Assistant Professor of Agricultural Chemistry in University of California. May, 1889.

Albert P. Low, B. A. Sc., LL. D., Ottawa, Canada; Deputy Minister, Department of Mines. December, 1905.

Hiram Deyer McCaskey, B. S., Washington, D. C.; U. S. Geological Survey. December, 1904.

Richard G. McConnell, A. B., Ottawa, Canada; Geologist on Geological and Natural History Survey of Canada. May, 1889.

James Rieman Macfarlane, A. B., 100 Diamond St., Pittsburg, Pa. August, 1891.

*W J McGee, LL. D., Washington, D. C.; Inland Waterways Commission.

William McInnes, A. B., Ottawa, Canada; Geologist, Geological and Natural History Survey of Canada. May, 1889.

Peter McKellar, Fort William, Ontario, Canada. August, 1890.

Curtis F. Marbut, A. M., Columbia, Mo.; Professor of Geology in State University and Assistant on Missouri Geological Survey. August, 1897.

VERNON F. MARSTERS, A. M., Apartado 856, Lima, Peru. August, 1892.

GEORGE CURTIS MARTIN, Ph. D., Washington, D. C.; U. S. Geological Survey. June, 1902.

EDWARD B. MATHEWS, Ph. D., Baltimore, Md.; Professor of Mineralogy and Petrography in Johns Hopkins University. August, 1895.

W. D. MATTHEW, Ph. D., New York City; Associate Curator of Vertebrate Paleontology, American Museum of Natural History. December, 1903.

P. H. MELL, M. E., Ph. D., 165 East 10th St., Atlanta, Ga. December, 1888.

WALTER C. MENDENHALL, B. S., Washington, D. C.; Geologist, U. S. Geological Survey. June, 1902.

JOHN C. MERRIAM, Ph. D., Berkeley, Cal.; Instructor in Paleontology in University of California. August, 1895.

*FREDERICK J. H. MERRILL, Ph. D., Nogales, Arizona.

GEORGE P. MERRILL, Ph. D., Washington, D. C.; Curator of Department of Lithology and Physical Geology in U. S. National Museum. December, 1888.

ARTHUR M. MILLER, A. M., Lexington, Ky.; Professor of Geology, State University of Kentucky. December, 1897.

BENJAMIN L. MILLER, Ph. D., South Bethlehem, Pa.; Professor of Geology, Lehigh University. December, 1904.

WILLET G. MILLER, M. A., Toronto, Canada; Provincial Geologist of Ontario. December, 1902.

HENRY MONTGOMERY, Ph. D., Toronto, Canada; Curator of Museum, University of Toronto. December, 1904.

*FRANK L. NASON, A. B., West Haven, Conn.

DAVID HALE NEWLAND, B. A., Albany, N. Y.; Assistant State Geologist. December, 1906.

JOHN F. NEWSOM, Ph. D., Stanford University, Cal.; Associate Professor of Mining in Leland Stanford, Jr., University. December, 1899.

WILLIAM H. NILES, Ph. D., M. A., Boston, Mass.; Professor Emeritus of Geology, Massachusetts Institute of Technology; Professor of Geology, Wellesley College. August, 1891.

WILLIAM H. NORTON, M. A., Mount Vernon, Iowa; Professor of Geology in Cornell College. December, 1895.

CHARLES J. NORWOOD, Lexington, Ky.; Professor of Mining, State University of Kentucky. August, 1894.

IDA HELEN OGILVIE, A. B., Ph. D., New York City; Tutor in Geology, Barnard College, Columbia University. December, 1906.

CLEOPHAS C. O'HARRA, Ph. D., Rapid City, S. Dak.; Professor of Mineralogy and Geology, South Dakota School of Mines. December, 1904.

EZEQUIEL ORDONEZ, 2 a General Prine, Mexico, D. F., Mex. August, 1896.

*AMOS O. OSBORN, Waterville, Oneida county, N. Y.

HENRY F. OSBORN, Sc. D., New York City; President of the American Museum of Natural History. August, 1894.

CHARLES PALACHE, B. S., Cambridge, Mass.; Instructor in Mineralogy, Harvard University. August, 1897.

WILLIAM A. PARKS, B. A., Ph. D., Toronto, Canada; Associate Professor of Geology, University of Toronto. December, 1906.

*Horace B. Patton, Ph. D., Golden, Colo.; Professor of Geology and Mineralogy in Colorado School of Mines.

Frederick B. Peck, Ph. D., Easton, Pa.; Professor of Geology and Mineralogy. Lafayette College. August, 1901.

David Pearce Penhallow, B. S., M. S., Sc. D., Montreal, Canada; Professor of Botany in McGill University. December, 1907.

Richard A. F. Penrose, Jr., Ph. D., 460 Bullitt Building, Philadelphia, Pa. May, 1889.

George H. Perkins, Ph. D., Burlington, Vt.; State Geologist; Professor of Geology, University of Vermont. June, 1902.

Joseph H. Perry, 276 Highland St., Worcester, Mass. December, 1888.

Louis V. Pirsson, Ph. D., New Haven, Conn.; Professor of Physical Geology Sheffield Scientific School of Yale University. August, 1894.

Joseph Hyde Pratt, Ph. D., Chapel Hill, N. C.; Mineralogist, North Carolina Geological Survey. December, 1898.

*Charles S. Prosser, M. S., Columbus, Ohio; Professor of Geology in Ohio State University.

*Raphael Pumpelly, Newport, R. I.

Albert Homer Purdue, B. A., Fayetteville, Ark.; Professor of Geology, University of Arkansas. December, 1904.

Frederick Leslie Ransome, Ph. D., Washington, D. C.; Geologist, U. S. Geological Survey. August, 1895.

Percy Edward Raymond, B. A., Ph. D., Pittsburgh, Pa.; Assistant Curator of Invertebrate Fossils in the Carnegie Museum. December, 1907.

Harry Fielding Reid, Ph. D., Baltimore, Md.; Professor of Geological Physics, Johns Hopkins University. December, 1892.

William North Rice, Ph. D., LL. D., Middletown, Conn.; Professor of Geology in Wesleyan University. August, 1890.

Charles H. Richardson, Ph. D., Syracuse, N. Y.; Assistant Professor of Geology and Mineralogy, Syracuse University. December, 1899.

George Burr Richardson, S. B., S. M., Ph. D., Washington, D. C.; U. S. Geological Survey. December, 1908.

Heinrich Ries, Ph. D., Ithaca, N. Y.; Professor of Economic Geology in Cornell University. December, 1893.

Rudolph Ruedemann, Ph. D., Albany, N. Y.; Assistant State Paleontologist. December, 1905.

Orestes H. St. John, 1141 Twelfth St., San Diego, Cal. May, 1889.

*Rollin D. Salisbury, A. M., Chicago, Ill.; Professor of General and Geographic Geology in University of Chicago.

Frederick W. Sardeson, Ph. D., Minneapolis, Minn.; Assistant Professor of Geology, University of Minnesota. December, 1892.

Thomas Edmund Savage, A. B., B. S., M. S., Urbana, Ill.; Department of Geology, University of Illinois. December, 1907.

Frank C. Schrader, M. S., A. M., Washington, D. C.; U. S. Geological Survey. August, 1901.

Charles Schuchert, New Haven, Conn.; Professor of Paleontology, Yale University. August, 1895.

William B. Scott, Ph. D., 56 Bayard Ave., Princeton, N. J.; Blair Professor of Geology in Princeton University. August, 1892.

ARTHUR EDMUND SEAMAN, B. S., Houghton, Mich.; Professor of Mineralogy and Geology, Michigan College of Mines. December, 1904.

HENRY M. SEELY, M. D., Middlebury, Vt.; Professor of Geology in Middlebury College. May, 1899.

ELIAS H. SELLARDS, Ph. D., Tallahassee, Fla.; State Geologist. December, 1905.

JOAQUIM CANDIDO DA COSTA SEÑA, Ouro Preto, Brazil; Director of the State School of Mines and Professor of Mineralogy and Geology. December, 1908.

GEORGE BURBANK SHATTUCK, Ph. D., Poughkeepsie, N. Y.; Professor of Geology in Vassar College. August, 1899.

SOLON SHEDD, A. B., Pullman, Wash.; Professor of Geology and Mineralogy, Washington Agricultural College. December, 1904.

EDWARD M. SHEPARD, Sc. D., Springfield, Mo.; Professor of Geology, Drury College. August, 1901.

WILL H. SHERZER, M. S., Ypsilanti, Mich.; Professor in State Normal School, December, 1890.

BOHUMIL SHIMEK, C. E., M. S., Iowa City, Iowa; Professor of Physiological Botany, University of Iowa. December, 1904.

*FREDERICK W. SIMONDS, Ph. D., Austin, Texas; Professor of Geology in University of Texas.

WILLIAM JOHN SINCLAIR, B. S., Ph. D., Princeton, N. J.; Instructor in Princeton University. December, 1906.

EARLE SLOAN, Charleston, S. C.; State Geologist of South Carolina. December, 1908.

*EUGENE A. SMITH, Ph. D., University, Tuscaloosa county, Ala.; State Geologist and Professor of Chemistry and Geology in University of Alabama.

FRANK CLEMES SMITH, E. M., Richland Center, Wis. December, 1898.

GEORGE OTIS SMITH, Ph. D., Washington, D. C.; Director, U. S. Geological Survey. August, 1897.

WILLIAM S. T. SMITH, Ph. D., 839 Lake St., Reno, Nev.; Associate Professor of Geology and Mineralogy, University of Nevada. June, 1902.

*JOHN C. SMOCK, Ph. D., Trenton, N. J.

CHARLES H. SMYTH, JR., Ph. D., Princeton, N. J.; Professor of Geology in Princeton University. August, 1892.

HENRY L. SMYTH, A. B., Cambridge, Mass.; Professor of Mining and Metallurgy in Harvard University. August, 1894.

ARTHUR COE SPENCER, B. S., Ph. D., Washington, D. C.; Assistant Geologist, U. S. Geological Survey. December, 1896.

*J. W. SPENCER, Ph. D., 2019 Hillyer Place, Washington, D. C.

JOSIAH E. SPURR, A. B., A. M., 165 Broadway, New York City. December, 1894.

JOSEPH STANLEY-BROWN, Cold Spring Harbor, Long Island, N. Y. August, 1892.

TIMOTHY WILLIAM STANTON, B. S., U. S. National Museum, Washington, D. C.; Assistant Paleontologist, U. S. Geological Survey. August, 1891.

*JOHN J. STEVENSON, Ph. D., LL. D., 568 West End Ave., New York City.

GEORGE WILLIS STOSE, B. S., Washington, D. C.; U. S. Geological Survey. December, 1908.

William J. Sutton, B. S., E. M., Victoria, B. C.; Geologist to E. and N. Railway Co. August, 1901.

Charles Kephart Swartz, A. B., Ph. D., Baltimore, Md.; Associate Professor of Geology in Johns Hopkins University. December, 1908.

Joseph A. Taff, B. S., Palo Alto, Cal.; Assistant Geologist, U. S. Geological Survey. August, 1895.

James E. Talmage, Ph. D., Salt Lake City, Utah; Professor of Geology in University of Utah. December, 1897.

Ralph S. Tarr, Ithaca, N. Y.; Professor of Dynamic Geology and Physical Geography in Cornell University. August, 1890.

Frank B. Taylor, Fort Wayne, Ind. December, 1895.

William G. Tight, M. S., Albuquerque, N. Mex. August, 1897.

*James E. Todd, A. M., 113 Park St., Lawrence, Kas.; Assistant Geologist, U. S. Geological Survey.

*Henry W. Turner, B. S., Room 709, Mills Building, San Francisco, Cal.

Joseph B. Tyrrell, M. A., B. Sc., Room 534, Confederation Life Bldg., Toronto, Canada. May, 1889.

Johan A. Udden, A. M., Rock Island, Ill.; Professor of Geology and Natural History in Augustana College. August, 1897.

Edward O. Ulrich, D. Sc., Washington, D. C.; Assistant Geologist, U. S. Geological Survey. December, 1903.

*Warren Upham, A. M., Saint Paul, Minn.; Librarian Minnesota Historical Society.

*Charles R. Van Hise, M. S., Ph. D., Madison, Wis.; President University of Wisconsin; Geologist, U. S. Geological Survey.

Frank Robertson Van Horn, Ph. D., Cleveland, Ohio; Professor of Geology and Mineralogy, Case School of Applied Science. December, 1898.

Gilbert van Ingen, Princeton, N. J.; Curator of Invertebrate Paleontology and Assistant in Geology, Princeton University. December, 1904.

Thomas Wayland Vaughan, B. S., A. M., Washington, D. C.; Assistant Geologist, U. S. Geological Survey. August, 1896.

Arthur Clifford Veach, Washington, D. C.; Geologist, U. S. Geological Survey. December, 1906.

*Anthony W. Vogdes, 2425 First St., San Diego, Cal.; Brigadier General, U. S. A. (Retired).

*M. Edward Wadsworth, Ph. D., Pittsburgh, Pa.; Dean of the School of Mines in the University of Pittsburgh.

*Charles D. Walcott, LL. D., Washington, D. C.; Secretary Smithsonian Institution.

Thomas L. Walker, Ph. D., Toronto, Canada; Professor of Mineralogy and Petrography, University of Toronto. December, 1903.

Charles H. Warren, Ph. D., Boston, Mass.; Instructor in Geology, Massachusetts Institute of Technology. December, 1901.

Henry Stephens Washington, Ph. D., Locust, Monmouth Co., N. J.; August, 1896.

Thomas L. Watson, Ph. D., Charlottesville, Va.; Professor of Geology in University of Virginia. June, 1900.

Walter H. Weed, E. M., Norwalk, Conn. May, 1889.

Fred. Boughton Weeks, Washington, D. C.; Assistant Geologist, U. S. Geological Survey. December, 1903.

Samuel Weidman, Ph. D., Madison, Wis.; Geologist, Wisconsin Geological and Natural History Survey. December, 1903.

Stuart Weller, B. S., Chicago, Ill.; Associate Professor of Paleontologic Geology, University of Chicago. June, 1900.

Lewis G. Westgate, Ph. D., Delaware, Ohio; Professor of Geology, Ohio Wesleyan University.

Thomas C. Weston, care of A. Patton, Levis, Quebec, Canada. August, 1893.

David White, B. S., U. S. National Museum, Washington, D. C.; Geologist, U. S. Geological Survey. May, 1889.

*Israel C. White, Ph. D., Morgantown, W. Va.

*Robert P. Whitfield, A. M., New York City; Curator Emeritus of Geology and Invertebrate Paleontology, American Museum of Natural History.

Frank A. Wilder, Ph. D., North Holston, Smyth Co., Va. December, 1905.

*Edward H. Williams, Jr., A. C., E. M., Andover, Mass.

*Henry S. Williams, Ph. D., Ithaca, N. Y.; Professor of Geology and Head of Geological Department, Cornell University.

Ira A. Williams, M. Sc., Ames, Iowa; Teacher Iowa State College. December, 1905.

Bailey Willis, Washington, D. C.; U. S. Geological Survey. December, 1889.

Samuel W. Williston, Ph. D., M. D., Chicago, Ill.; Professor of Paleontology, University of Chicago. December, 1889.

Arthur B. Willmott, M. A., 24 Adelaide St., W., Toronto, Canada. December, 1899.

Alfred W. G. Wilson, Ph. D., Mines Branch, Department of Mines, Ottawa, Canada. June, 1902.

Alexander N. Winchell, Doct. U. Paris, Madison, Wis.; Professor of Geology and Mineralogy, University of Wisconsin. August, 1901.

*Horace Vaughn Winchell, 505 Palace Building, Minneapolis, Minn.

*Newton H. Winchell, A. M., 501 East River Road, Minneapolis, Minn.

*Arthur Winslow, B. S., 131 State St., Boston, Mass.

John E. Wolff, Ph. D., Cambridge, Mass.; Professor of Petrography and Mineralogy in Harvard University and Curator of the Mineralogical Museum. December, 1889.

Joseph E. Woodman, S. D., New York City; Professor of Geology in New York University. December, 1905.

Robert S. Woodward, C. E., Washington, D. C.; President of the Carnegie Institution of Washington. May, 1889.

Jay B. Woodworth, B. S., 24 Langdon St., Cambridge, Mass.; Assistant Professor of Geology, Harvard University. December, 1895.

Frederic E. Wright, Ph. D., Washington, D. C.; Geophysical Laboratory, Carnegie Institution. December, 1903.

*G. Frederick Wright, D. D., Oberlin, Ohio; Professor in Oberlin Theological Seminary.

George A. Young, Ph. D., Ottawa, Canada; Geologist, Geological Survey of Canada. December, 1905.

FELLOWS-ELECT

William Clinton Alden, A. B., A. M., Ph. D., Washington, D. C. Assistant Geologist, U. S. Geological Survey. December, 1909.

Wallace Walter Atwood, B. S., Ph. D., Chicago, Illinois. Instructor at University of Chicago and Assistant Geologist, U. S. Geological Survey. December, 1909.

Edson Sunderland Bastin, A. B., A. M., Washington, D. C. Assistant Geologist, U. S. Geological Survey. December, 1909.

Edward Wilber Berry, Baltimore, Maryland. Instructor in Paleontology, Johns Hopkins University. December, 1909.

Willis Stanley Blatchley, A. B., A. M., State House, Indianapolis, Indiana. State Geologist of Indiana. December, 1909.

Henry Andrew Buehler, B. S., Rolla, Missouri. State Geologist of Missouri. December, 1909.

Fred Harvey Hall Calhoun, B. S., Ph. D., Clemson College, South Carolina. Professor of Geology and Mineralogy, Clemson College, and Assistant Geologist, U. S. Geological Survey. December, 1909.

Arthur Louis Day, B. A., Ph. D., Washington, D. C. Director, Geophysical Laboratory, Carnegie Institution of Washington. December, 1909.

Frank Wilbridge De Wolf, S. B., Urbana, Illinois. Assistant State Geologist of Illinois and Assistant Geologist, U. S. Geological Survey. December, 1909.

James Walter Goldthwait, A. B., A. M., Ph. D., Hanover, New Hampshire. Assistant Professor of Geology in Dartmouth College and head of department. December, 1909.

Baird Halberstadt, Pottsville, Pennsylvania. Engineer and Geologist. December, 1909.

Oscar H. Hershey, Kellogg, Idaho. December, 1909.

Frederick Brewster Loomis, B. A., Ph. D., Amherst, Massachusetts. Professor of Comparative Anatomy in Amherst College. December, 1909.

Richard Swann Lull, B. S., M. S., Ph. D., New Haven, Connecticut. Assistant Professor of Vertebrate Paleontology, Yale University. December, 1909.

George Rogers Mansfield, B. S., A. M., Ph. D., Evanston, Illinois. Assistant Professor of Geology, Northwestern University. December, 1909.

Lawrence Martin, A. B., A. M., Madison, Wisconsin. Instructor in Geology, University of Wisconsin. December, 1909.

Samuel Washington McCallie, Ph. B., Atlanta, Georgia. State Geologist of Georgia. December, 1909.

William John Miller, S. B., Ph. D., Clinton, New York. Professor of Geology and Mineralogy in Hamilton College. December, 1909.

Malcolm John Munn, Washington, D. C. Assistant Geologist, U. S. Geological Survey. December, 1909.

Edward Orton, Jr., E. M., Columbus, Ohio. Assistant Geologist, Geological Survey of Ohio. December, 1909.

Philip S. Smith, A. B., A. M., Ph. D., Washington, D. C. Assistant Geologist, U. S. Geological Survey. December, 1909.

Warren Du Pré Smith, B. S., A. M., Ph. D., Manila, Philippine Islands. Chief of the Mining Bureau. December, 1909.

Cyrus Fisher Tolman, Jr., B. S., Tucson, Arizona. Professor of Geology and Mining in the University of Arizona. December, 1909.

Charles Will Wright, B. S., M. E., Washington, D. C. Assistant Geologist, U. S. Geological Survey. December, 1909.

FELLOWS DECEASED

*Indicates Original Fellow (see article III of Constitution)

*Charles A. Ashburner, M. S., C. E. Died December 24, 1889.
Charles E. Beecher, Ph. D. Died February 14, 1904.
Amos Bowman. Died June 18, 1894.
*J. H. Chapin, Ph. D. Died March 14, 1892.
*Edward W. Claypole, D. Sc. Died August 17, 1901.
George H. Cook, Ph. D., LL. D. Died September 22, 1889.
*Edward D. Cope, Ph. D. Died April 12, 1897.
Antonio Del Castillo. Died October 28, 1895.
*James D. Dana, LL. D. Died April 14, 1895.
George M. Dawson, D. Sc. Died March 2, 1901.
Sir J. William Dawson, LL. D. Died November 19, 1899.
*William B. Dwight, Ph. B. Died August 29, 1906.
*George H. Eldridge, A. B. Died June 29, 1905.
*Albert E. Foote. Died October 10, 1895.
*Persifor Frazer. Died April 7, 1909.
*Homer T. Fuller. Died August 14, 1908.
N. J. Giroux, C. E. Died November 30, 1890.
*James Hall, LL. D. Died August 7, 1898.
John B. Hatcher, Ph. B. Died July 3, 1904.
*Robert Hay. Died December 14, 1895.
*Angelo Heilprin. Died July 17, 1907.
David Honeyman, D. C. L. Died October 17, 1889.
Thomas Sterry Hunt, D. Sc., LL. D. Died February 12, 1892.
*Alpheus Hyatt, B. S. Died January 15, 1902.
*Joseph F. James, M. S. Died March 29, 1897.
Wilbur C. Knight, B. S., A. M. Died July 28, 1903.
Ralph D. Lacoe. Died February 5, 1901.
Daniel W. Langton. Died June 21, 1909.
*Joseph Le Conte, M. D., LL. D. Died July 6, 1901.
*J. Peter Lesley, LL. D. Died June 2, 1903.
Henry McCalley, A. M., C. E. Died November 20, 1904.
Oliver Marcy, LL. D. Died March 19, 1899.
Othniel C. Marsh, Ph. D., LL. D. Died March 18, 1899.
James E. Mills, B. S. Died July 25, 1901.
*Henry B. Nason, M. D., Ph. D., LL. D. Died January 17, 1895.
*Peter Neff, M. A. Died May 11, 1903.
*John S. Newberry, M. D., LL. D. Died December 7, 1892.
*Edward Orton, Ph. D., LL. D. Died October 16, 1899.
*Richard Owen, LL. D. Died March 24, 1890.
Samuel L. Penfield. Died August 14, 1906.
*Franklin Platt. Died July 24, 1900.
William H. Pettee, A. M. Died May 26, 1904.
*John Wesley Powell, LL. D. Died September 23, 1902.
*Israel C. Russell, LL. D. Died May 1, 1906.
*James M. Safford, M. D., LL. D. Died July 3, 1907.

*Charles Schaeffer, M. D. Died November 23, 1903.
*Nathaniel S. Shaler, LL. D. Died April 10, 1906.
Charles Wachsmuth. Died February 7, 1896.
Theodore G. White, Ph. D. Died July 7, 1901.
*George H. Williams, Ph. D. Died July 12, 1894.
*J. Francis Williams, Ph. D. Died September 9, 1891.
*Alexander Winchell, LL. D. Died February 19, 1891.
Albert A. Wright, Ph. D. Died April 2, 1905.
William S. Yeates. Died February 19, 1908.

Summary

Original Fellows	58
Elected Fellows	252
Membership	310
Deceased Fellows	54

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 21, PP. 69-86 MARCH 31, 1910

PROCEEDINGS OF THE PRELIMINARY MEETING OF THE PALEONTOLOGICAL SOCIETY, HELD AT BALTIMORE, MARYLAND, DECEMBER 30, 1908, AND ALSO PROCEEDINGS OF THE FIRST ANNUAL MEETING HELD AT CAMBRIDGE, MASSACHUSETTS, DECEMBER 29, 1909.

HERDMAN F. CLELAND, *Secretary*

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PRELIMINARY MEETING FOR THE ORGANIZATION OF A PALEONTOLOGICAL SOCIETY

The meeting for the purpose of organizing a paleontological society was called to order by Prof. Charles Schuchert, in the Geological Laboratory of Johns Hopkins University, Baltimore, at 9.10 a. m., December 30, 1908. Mr. T. W. Stanton was appointed Secretary *pro tempore.*

The following persons were present and by their signatures signified their intention to take part in organizing the Paleontological Society of America: H. M. Ami, Ralph Arnold, R. M. Bagg, Jr., R. S. Bassler, J. W. Beede, E. W. Berry, E. C. Case, William Bullock Clark, John M. Clarke, Harold J. Cook, Edgar R. Cumings, August F. Foerste, J. W. Gidley, Charles W. Gilmore, A. W. Grabau, Edwin Kirk, F. H. Knowlton, E. B. Loomis, R. S. Lull, W. D. Matthew, Henry Fairfield Osborn, Charles S. Prosser, P. S. Raymond, E. S. Riggs, T. E. Savage, Charles Schuchert, H. W. Shimer, T. W. Stanton, E. O. Ulrich, Charles D. Walcott, Stuart Weller, David White, Henry S. Williams, S. W. Williston.

Professor Schuchert outlined the history of the movement for the organization of a paleontological society, and presented a preliminary plan drawn up by the temporary committee, of which he had acted as chairman. At the New Haven meeting of the Society of American Vertebrate Paleontologists, in 1907, there was a general discussion in which several members favored the formation of a society of broader scope, in which workers in all branches of paleontologic research could be united. As a result of this discussion and of a suggestion that grew out of it, Professor Schuchert invited Messrs. John M. Clarke, F. B. Loomis, William J. Sinclair, T. W. Stanton, E. O. Ulrich, C. D. Walcott, David White, and S. W. Williston to cooperate with him as a committee to consider ways and means of organizing a paleontological society. This committee sent out a circular to all the paleontologists of the country inviting them to vote on the general question of organization and on several details, such as whether the society should be independent or a section of the Geological Society of America, what kind of a publication is practicable, etcetera. The committee also issued the call for this meeting, and outlined a constitution modeled after that of the Geological Society. The principal features of the proposed constitution were presented to the meeting by the chairman.

On motion of Dr. C. D. Walcott, an executive committee on organization, with full power to act for the society, was formed, consisting of Charles Schuchert, F. B. Loomis, S. W. Williston, David White, H. F. Osborn, and T. W. Stanton.

Prof. William Bullock Clark, as a member of the Council of the Geological Society of America, read a resolution adopted by that Council, expressing sympathy with the movement to organize the paleontologists and suggesting a joint committee to adjust details of affiliation.

On motion, the Executive Committee of the Paleontological Society was empowered to act for the paleontologists with a committee to be appointed by the Council of the Geological Society of America to adjust relations with that Society.

The Executive Committee was authorized to elect the officers of the Society for 1909.

At 10 a. m. the meeting adjourned.

(Signed) T. W. Stanton,
Secretary pro tem.

Report of the Organization Committee of the Paleontological Society

Pursuant to the call of the chairman, the Executive Committee of the Paleontological Society met with a special committee of the Geological Society of America in the American Museum of Natural History, New York City, at 10 a. m., February 13, 1909, for the purpose of adjusting the relations between the two societies. There were present Messrs. F. B. Loomis, David White, and T. W. Stanton, representing the Paleontological Society of America, and Messrs. W. B. Clark, J. M. Clarke, H. E. Gregory, and E. O. Hovey, representing the Geological Society of America. W. B. Clark acted as chairman of the conference.

From the preliminary discussion it was evident that the majority of those interested in the organization of a paleontological society were in favor of making it a section of the Geological Society of America, as expressed in a previous vote, and that the Geological Society was willing to recognize such a section and to assist it by increasing facilities for publishing paleontologic papers and in other ways, so far as its financial condition would allow.

A provisional draft of a "Constitution and By-Laws of the Paleontological Society of America," based on those of the Geological Society and prepared by Professor Schuchert, was read by paragraphs and informally discussed, and amended so as to make it consistent with the form of organization agreed upon, namely, a section of the Geological Society of America.

On the suggestion of Dr. J. M. Clarke, it was decided to adopt "The Paleontological Society" as the name of the organization, the qualifying phrase "of America" being unnecessary, since there is no other paleontological society.

After the adjournment of the conference, the Executive Committee reassembled and ratified the Constitution and By-Laws as amended in the joint session.[1] Under the authority granted at the preliminary meeting in Baltimore on December 30, 1908, the committee proceeded to elect officers for the remainder of this year as follows:

President, J. M. Clarke.
First Vice-President, J. C. Merriam.
Second Vice-President, T. W. Stanton.
Third Vice-President, David White.
Treasurer, W. D. Matthew.
Secretary, H. F. Cleland.
Editor, C. R. Eastman.

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[1] The Constitution and By-Laws of the Paleontological Society are published as pages 77-82 of this volume.

It is understood that this board will hold office only until the close of the first annual meeting, and that in accordance with the provisions of the Constitution and By-Laws they must prepare and send out a list of nominations for their successors within thirty days.

It was also agreed that the selection of the First, Second, and Third Vice-Presidents, respectively, from the Vertebrate, Invertebrate, and Botanical Sections is not a permanent arrangement, but that the order of precedence should be changed from time to time.

Adjourned.

T. W. Stanton,
Secretary.

First Annual Meeting of the Paleontological Society

The first annual meeting of the Paleontological Society was called to order by President John M. Clarke at 10 o'clock a. m., Wednesday, December 29, 1909, in the Nash Lecture Hall of the Botanical Museum, Harvard University, Cambridge, Massachusetts.

Report of the Secretary

To the Members of The Paleontological Society:

During the year notices of the organization of The Paleontological Society, with a statement of the qualifications for membership, were sent to the paleontologists of Canada, Mexico, Brazil, and the United States. To these a prompt and encouraging reply was received from the majority of the paleontologists to whom the notices were sent.

As a result of these circular letters and of the correspondence carried on by members of the Council, the membership of the Society at present is as given in the accompanying list (pages 83-86).

The following resolutions were adopted by the Council:

Resolved, That the Council of the Paleontological Society invites the entire membership of the Society of American Vertebrate Paleontologists to enroll as members of the Paleontological Society; and further

Resolved, That the members of the Vertebrate Paleontological Society shall immediately on such adhesion and qualification be enrolled in the membership of the Paleontological Society without further formality.

Election of officers.—At the meeting of the Council held at the rooms of the President, in Copley Square Hotel, December 28, 1909, the ballots were opened. Forty-two votes were received, all of which were cast for the officers who were nominated by the Council.

The officers and Council for the year 1910 are as follows:

President:

CHARLES SCHUCHERT, New Haven, Conn.

First Vice-President:

E. O. ULRICH, Washington, D. C.

Second Vice-President:

S. W. WILLISTON, Chicago, Ill.

Third Vice-President:

F. H. KNOWLTON, Washington, D. C.

Secretary:

HERDMAN F. CLELAND, Williamstown, Mass.[2]

Treasurer:

W. D. MATTHEW, New York City.

Editor:

CHARLES R. EASTMAN, Cambridge, Mass.

Election of members.—All persons proposed for membership were elected without opposition. The list will be found on page 86.

Program.—After the presidential address by Dr. John M. Clarke, a "Conference on the Aspects of Paleontology" was held, at which papers on assigned topics were read by members of the Society by invitation of the Council, as follows:

ADEQUACY OF THE PALEONTOLOGIC RECORD

BY R. S. BASSLER

INTERDEPENDENCE OF STRATIGRAPHY AND PALEONTOLOGY

BY W. J. SINCLAIR AND E. O. ULRICH

BIOLOGIC PRINCIPLES OF PALEOGEOGRAPHY

BY CHARLES SCHUCHERT

PALEONTOLOGIC EVIDENCES OF CLIMATE

BY T. W. STANTON AND DAVID WHITE

MIGRATION

BY HENRY S. WILLIAMS AND ARTHUR HOLLICK

[2] Herdman F. Cleland resigned, and R. S. Bassler, of Washington, D. C., was elected by the Council to fill the vacancy.

PALEONTOLOGIC EVIDENCES OF ADAPTIVE RADIATION

BY H. FAIRFIELD OSBORN

ANATOMY AND PHYSIOLOGY IN EXTINCT ORGANISMS

BY CHARLES R. EASTMAN AND RUDOLPH RUEDEMANN

CONTRIBUTIONS TO MORPHOLOGY FROM PALEONTOLOGY

BY WILLIAM BULLOCK CLARK

EMBRYOLOGY AND PALEONTOLOGY

BY RICHARD S. LULL AND WILLIAM H. DALL

ONTOGENY AND PALEONTOLOGY

BY F. B. LOOMIS AND AMADEUS W. GRABAU

PHYLOGENY AND PALEONTOLOGY

BY ROBERT T. JACKSON AND D. P. PENHALLOW

PALEONTOLOGIC EVIDENCES OF RECAPITULATION

BY E. R. CUMMINGS AND L. HUSSAKOF

ISOLATION IN PALEONTOLOGY

BY JOHN M. CLARKE

CONTINUITY OF DEVELOPMENT FROM THE PALEONTOLOGIC STANDPOINT

BY T. WAYLAND VAUGHAN

PALEONTOLOGY OF MAN

BY S. W. WILLISTON

Then were read general papers, as follows:

VARANOSAURUS SPECIES, A PERMIAN PELYCOSAUR

BY S. W. WILLISTON

Discussed by H. F. Osborn, W. J. Sinclair, and W. J. Holland.

THE STRUCTURE OF THE SAUROPOD DINOSAURS

BY W. J. HOLLAND

Discussed by S. W. Williston.

PHYLOGENY OF THE FELIDÆ

BY W. D. MATTHEW

(By title)

OSTEOLOGY AND RELATIONSHIPS OF PARAMYS AND THE AFFINITIES OF THE ISCHYROMYIDÆ

BY W. D. MATTHEW

(By title)

PHYLOGENETIC POSITION OF THE GENUS STEGOMYLUS

BY F. B. LOOMIS

THE ARMOR OF STEGOSAURUS

BY R. S. LULL

Discussed by H. F. Osborn and W. J. Holland.

RESTORATION OF PALEOLITHIC MAN

BY R. S. LULL

NEW GENUS OF PERMIAN REPTILE

BY S. W. WILLISTON

PRINCIPAL CHARACTER OF THE CHELYDROSAURIA, A SUB-ORDER OF TEMNOSPONDYTE AMPHIBIANS FROM THE TEXAS PERMIAN

BY S. W. WILLISTON

SKULL OF TYRANNOSAURUS

BY H. F. OSBORN

ANDERSON'S METHODS OF PHOTOGRAPHY IN VERTEBRATE PALEONTOLOGY

BY H. F. OSBORN

CORRELATION OF THE PLEISTOCENE OF EUROPE AND AMERICA

BY H. F. OSBORN

LARAMIE FLORA OF SOUTHWESTERN WYOMING

BY F. H. KNOWLTON

(By title)

PERMIAN FLORAS IN THE WESTERN "RED BEDS" [3]

BY DAVID WHITE

Discussed by C. Schuchert, J. W. Beede, J. M. Clarke, and E. O. Ulrich.

ORDOVICIC-SILURIC SECTION OF THE MINGAN AND ANTICOSTI ISLANDS

BY CHARLES SCHUCHERT AND W. H. TWENHOFEL

Discussed by E. O. Ulrich and A. W. Grabau.

[3] From the Geological Society's program.

PERSISTENCE OF FLUCTUATING VARIATIONS AS ILLUSTRATED BY THE GENUS RHIPIDOMELLA

BY HENRY S. WILLIAMS

MIGRATIONS AND THE SHIFTING OF DEVONIAN FAUNAS

BY HENRY S. WILLIAMS

(By title)

INTRACOLONIAL ACCELERATION AND RETARDATION AND ITS BEARING ON SPECIES

BY AMADEUS W. GRABAU

FAUNA OF THE GIRARDEAU LIMESTONE AND OF THE EDGEWOOD FORMATION

BY T. E. SAVAGE

PHYLOGENY OF CERTAIN CERITHIIDÆ

BY ELVIRA WOOD

MODE OF LIFE OF THE EURYPTERIDA

BY JOHN M. CLARKE AND RUDOLPH RUEDEMANN

PLIOCENE AND PLEISTOCENE FORAMINIFERA FROM CALIFORNIA

BY RUFUS M. BAGG, JR.

(By title)

INTERNAL CHARACTERS OF SOME MISSISSIPPIAN RHYNCHONELLOID SHELLS

BY STUART WELLER

(By title)

NEW CYSTID FROM THE CLINTON FORMATION OF ONTARIO

BY W. A. PARKS

SOME NEW FOSSILS FROM THE CAMBRIAN OF SOUTH ATTLEBORO, MASS.

BY W. B. HALL[4]

NOTES ON THE UPPER CARBONIFEROUS IN SOUTHEAST NEW MEXICO AND WEST TEXAS

BY G. B. RICHARDSON

CORRELATION OF THE GUADALUPIAN AND KANSAS SECTIONS

BY J. W. BEEDE

HERDMAN F. CLELAND,
Secretary.

[4] Introduced by R. S. Lull.

CONSTITUTION AND BY-LAWS OF THE PALEONTOLOGICAL SOCIETY

CONSTITUTION

Article I

NAME

This Society shall be known as The Paleontological Society. It is affiliated with and forms a section of the Geological Society of America. The two societies shall, as a rule, meet together.

Article II

OBJECT

The object of this Society is the promotion of the Science of Paleontology.

Article III

MEMBERSHIP

The Society shall be composed of Fellows, Members, Correspondents, and Patrons.

1. Fellows shall be persons who have published results of paleontological research, and who upon nomination by the Council have been duly elected to fellowship by the Geological Society of America.
2. Members shall be persons not Fellows who are engaged or interested in paleontological work.
3. Correspondents shall be persons distinguished for their attainments in Paleontology and not resident in North America.
4. Patrons shall be persons who have bestowed important favors upon the Society. Election to patronship carries with it the rights and privileges of Members.
5. Fellows, Members, and Patrons are entitled to vote, but only Fellows are eligible to office in this Society.

Article IV

OFFICERS

1. The Officers of the Society are a President, three Vice-Presidents, a Secretary, a Treasurer, and an Editor.

These officers constitute an Executive Committee to be called the Council.

2. The President shall discharge the usual duties of a presiding officer at all meetings of the Society and of the Council. He shall take cognizance of the acts of the Society and of its officers, and cause the provisions of the Constitution and By-Laws to be faithfully carried into effect. The President shall also represent The Paleontological Society in the Council of the Geological Society of America.
3. The Vice-Presidents, in the order of their precedence, shall assume the duties of President in case of the absence or disability of the latter.

The three Vice-Presidents represent respectively the three chief branches of paleontology, and it shall be the duty of each to look after the interests and preside at the meetings of the section which he represents.

4. The Secretary shall keep the records of the proceedings of the Society, and a complete list of the Fellows, Members, Correspondents, and Patrons, with the dates of their election to and separation from the Society. He shall also be the Secretary of the Council.

The Secretary shall cooperate with the President in attention to the ordinary affairs of the Society. He shall attend to the preparation, printing, and mailing of circulars, blanks, and notifications of elections and meetings. He shall superintend other printing ordered by the Society or by the President, and shall have charge of its distribution, under the direction of the Council.

The Secretary, unless other provision be made, shall act as Librarian, and as Custodian of the property of the Society, except as provided for in Article IV, section 6.

5. The Treasurer shall have the custody of all funds of the Society except the fees of Fellows. He shall keep account of receipts and disbursements in detail, and this shall be audited as hereinafter provided.

6. The Editor shall supervise all matters connected with the publication of the transactions of the Society under the direction of the Council. He shall also be the keeper of all publications sent to the Society.

7. The Council is clothed with executive authority and with the legislative powers of the Society in the intervals between its meetings; but no extraordinary act of the Council shall remain in force beyond the next following stated meeting without ratification by the Society. The Council shall have control of the publications of the Society, under provisions of the By-Laws and of resolutions from time to time adopted. They shall receive nominations for Fellows, Members, Correspondents, and Patrons, and, on approval by them, shall submit such nominations to the Society for action. They shall have power to fill vacancies *ad interim* in any of the offices of the Society not otherwise provided for.

8. *Terms of Office.*—The President and Vice-Presidents shall be elected annually. The President shall not be eligible for re-election until after an interval of three years from retirement from office. A Vice-President is eligible for re-election not more than once within such interval.

The Secretary, Treasurer, and Editor shall be eligible to re-election without limitation.

Article V

VOTING AND ELECTIONS

1. All elections shall be by ballot. To elect a Fellow, Member, Correspondent, or Patron, or impose any special tax, shall require the assent of nine-tenths of all persons voting.

2. Voting by letter may be allowed.

3. *Election to Membership.*—Nominations for all classes of membership must be made by two Fellows according to a form to be provided by the Council. One of these Fellows must be personally acquainted with the nominee and his qualifications for membership. The Council will submit the nominations received by them, if approved, to a vote of the Society in the manner provided in the By-Laws. The result may be announced at any stated meeting; after which notice shall be sent out to the elect.

4. *Election of Officers.*—Nominations for office shall be made by the Council or otherwise as provided for in the By-Laws. The nominations shall be submitted to a vote of the Society in the same manner as nominations for membership. The results shall be announced at the annual meeting; and the officers thus elected shall enter upon duty at the adjournment of the meeting.

Article VI

MEETINGS

1. The Society shall hold at least one stated meeting a year in the winter season. The date and place of this meeting shall be fixed by the Council, and announced each year within three months after the adjournment of the preceding winter meeting. The program of such meeting shall be determined by the Council in conjunction with the Council of the Geological Society of America and announced beforehand, in its general features. The details of the daily sessions shall be arranged by the Council of this Society.

2. The winter meeting shall be regarded as the annual meeting.

3. Special meetings of the Society as a whole or of any of its sections as sectional meetings may be called by the Council, and must be called upon the written request of ten Fellows, for a general meeting and of five Fellows for any of its sections.

4. The stated meetings of the Council shall be held coincidently with the stated meeting of the Society. Special meetings may be called by the President at such times as he may deem necessary.

5. *Quorum.*—At meetings of the Society a majority of those registered in attendance shall constitute a quorum. Four shall constitute a quorum of the Council.

Article VII

PUBLICATIONS

The publications of the Society shall be under the immediate control of the Council.

Article VIII

AMENDMENTS

1. This Constitution may be amended at any winter meeting by a three-fourths vote of all the Fellows, provided that the proposed amendment shall have been submitted in print to all Fellows at least three months previous to the meeting.

2. By-Laws may be made or amended by a majority vote of the Fellows present and voting at any annual meeting, provided that printed notice of the proposed amendment or by-law shall have been given to all Fellows at least three months before the meeting.

BY-LAWS

Chapter I

MEMBERSHIP

1. All Fellows of the Geological Society of America in good standing whose work is primarily in paleontology may, upon application to the Council of this Society, be elected without additional dues as Fellows of The Paleontological

Society. Such Fellows, if Life Members of the Geological Society, will have no further dues to pay in The Paleontological Society.

2. No person shall be accepted as a Fellow of The Paleontological Society unless he pay to the Geological Society of America the initiation fee and the dues for the year within three months after notification of his election. The initiation fee of Fellows shall be ten (10) dollars and the annual dues ten (10) dollars, payable on or before the annual meeting in advance; but a single prepayment of one hundred (100) dollars shall be accepted as commutation for life.

The annual dues for Members shall be three (3) dollars. No person shall be accepted as a Member unless he pay the dues for the year within three months after notification of his election. The annual dues are payable to The Paleontological Society on or before the annual meeting.

3. An arrearage in payment of annual dues shall deprive a Fellow or Member of the privilege of taking part in the management of the Society and of receiving the publications of the Society. An arrearage continuing over two (2) years shall be construed as notification of withdrawal.

4. Any person eligible under Article III of the Constitution may be elected Patron upon the payment of one thousand (1,000) dollars to the Society.

Chapter II

OFFICIALS

1. The President shall countersign, if he approves, all duly authorized accounts and orders drawn on the Treasurer for the disbursement of money.

2. The Secretary, until otherwise ordered by the Society, shall perform the duties of Editor, Librarian, and Custodian of the property of the Society.

3. The Society may elect an Assistant Secretary.

4. The Treasurer shall give bonds, with two good sureties approved by the Council, in the sum of one thousand dollars, for the faithful and honest performance of his duties and the safe-keeping of the funds of the Society. He may deposit the funds in bank at his discretion, but shall not invest them without authority of the Council. His accounts shall be balanced as on the thirtieth day of November of each year.

5. The minutes of the proceedings of the Council shall be subject to call by the Society.

6. The Council may transact its business by correspondence during the intervals between its stated meetings; but affirmative action by a majority of the Council shall be necessary in order to make action by correspondence valid.

Chapter III

ELECTION OF MEMBERS

1. Nominations for all classes of membership may be proposed at any time on blanks to be supplied by the Secretary.

2. The form for nomination shall be as follows:

In accordance with his desire, we respectfully nominate for Fellow, Member, Correspondent, or Patron of The Paleontological Society:
Full name; degrees; address; occupation; branch of Paleontology now engaged in; work already done and publications made.
(Signed by at least two Fellows.)

The form when filled is to be transmitted to the Secretary.

3. The Secretary will bring all nominations before the Council, at the winter meeting of the Society. The Council will signify its approval or disapproval of each, and forward to the Council of the Geological Society of America all approved nominations to Fellowship.

4. At least a month before the stated winter meeting of the Society the Secretary shall mail a printed list of all approved nominees for membership to each Fellow and Member, accompanied by such information as may be necessary for intelligent voting, but an informal list of the candidates shall be sent to each Fellow and Member at least two weeks prior to distribution of the ballots.

5. The Fellows and Members receiving the list will signify their approval or disapproval of each nominee, and return the lists to the Secretary.

6. At the next stated meeting of the Council the Secretary shall present the lists and the Council will canvass the returns.

7. The Council, by unanimous vote of the members in attendance, may still exercise the power of rejection of any nominee whom new information shows to be unsuitable for membership.

8. At the next stated meeting of the Society the Council shall declare the results.

Chapter IV

ELECTION OF OFFICERS

1. The Council shall prepare a list of nominations for the several offices, which list will constitute the regular ticket. This ticket must be approved by a majority of the entire Council. The nominee for President shall not be a member of the Council.

2. The list shall be mailed to the Fellows and Members, for their information, at least nine months before the annual meeting. Any five Fellows may forward to the Secretary other nominations for any or all offices. All such nominations reaching the Secretary at least 40 days before the annual meeting shall be printed, together with the names of the nominators, as special tickets. The regular and special tickets shall then be mailed to the Fellows and Members at least 25 days before the annual meeting.

3. The Fellows and Members shall send their ballots to the Secretary in double envelopes, the outer envelope bearing the voter's name. At the winter meeting of the Council, the Secretary shall bring the returns of ballots before the Council for canvass, and during the winter meeting of the Society the Council shall declare the result.

4. In case a majority of all the ballots shall not have been cast for any candidate for any office, the Society shall by ballot at such winter meeting proceed to make an election for such office from the two candidates having the highest number of votes.

Chapter V

FINANCIAL METHODS

1. No pecuniary obligation shall be contracted without express sanction of the Society or the Council. But it is to be understood that all ordinary, incidental, and running expenses have the permanent sanction of the Society, without special action.

2. The creditor of the Society must present to the Treasurer a fully itemized bill, certified by the official ordering it, and approved by the President. The Treasurer shall then pay the amount out of any funds not otherwise appropriated, and the receipted bill shall be held as his voucher.

3. At each annual meeting, the President shall call upon the Society to choose two Fellows or Members, not members of the Council, to whom shall be referred the books of the Treasurer, duly posted and balanced to the close of November thirtieth, as specified in the By-Laws, Chapter II, section 4. The Auditors shall examine the accounts and vouchers of the Treasurer, and any member or members of the Council may be present during the examination. The report of the Auditors shall be rendered to the Society before the adjournment of the meeting, and the Society shall take appropriate action.

Chapter VI

PUBLICATIONS

1. The publications are in charge of the Council and under its control.

2. One copy of each publication shall be sent to each Fellow, Member, Correspondent, and Patron.

Chapter VII

THE PUBLICATION FUND

The Publication Fund shall consist of donations made in aid of publication.

Chapter VIII

ORDER OF BUSINESS

1. The Order of Business at winter meetings shall be as follows:

(1) Call to order by the presiding officer.
(2) Introductory ceremonies.
(3) Report of the Council (including report of the officers).
(4) Appointment of the Auditing Committee.
(5) Declaration of the vote for officers, and election by the meeting in case of failure to elect by the Society through transmitted ballots.
(6) Declaration of the vote for Fellows.
(7) Declaration of the vote for Members.
(8) Deferred business.
(9) New business.
(10) Announcements.
(11) Necrology.
(12) Reading of scientific papers.

2. At an adjourned session the order shall be resumed at the place reached on the previous adjournment, but new business will be in order before the reading of scientific papers.

3. At any Special Meeting the order of business shall be numbers (1), (2), (3), (10), followed by the special business for which the meeting was called.

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*Indicates the Fellows of the Society (see Article III of the Constitution, on page 77 of this volume).

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ORIGIN OF THE ALKALINE ROCKS[1]

BY REGINALD A. DALY

(*Presented in abstract before the Society December 30, 1909*)

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Definition

Alkaline rocks include two classes: first, those relatively rich in soda, in potash, or in both; and, secondly, those which, with relatively low total of alkalies, yet carry essential amounts of minerals specially characteristic of alkali-rich eruptives, such as nephelite, leucite, analcite, etcetera. Field (genetic) association is also a criterion generally used in separating any alkaline type from the subalkaline or lime-alkali group of igneous rocks. Thus, monzonite may not be rich in alkalies nor carry any feldspathoid, yet it is regarded as of the alkaline group largely because it is often in comagmatic relation to nephelite syenite or the alkaline feldspar syenites. For the same reason, camptonite, alnöite, limburgite, and melilite basalt with, on the average, only 4.1 to 5.4 per cent of alkalies for each, are considered as belonging in the alkaline groups, though no feldspathoid is an essential constituent of any one of these rocks. On the

[1] Manuscript received by the Secretary of the Society January 4, 1910.

other hand, liparite and dacite, with average alkalies of, respectively, 7.6 and 6.6 per cent, are placed in the subalkaline group because of their common independence of the nephelite syenites, phonolites, leucitic rocks, etcetera, in field occurrence. No single principle compels the separation of the two groups, and the difficulty of making it sharp is enhanced by the fact that there are plenty of rock species transitional between ideal alkaline types and standard types of the subalkaline group. Nevertheless, the separation so far actually made by Rosenbusch, Iddings, Loewinson-Lessing, Harker, and many others is about as definite as some of the divisions among the subalkaline rocks. For this paper the question as to how far the distinction is objective and justifiable need not be answered, though it will be seen that there are grounds for believing in a very close genetic connection between the two groups.

General Statement of the Investigation

This major classification of igneous rocks immediately raises the question of origins. Why are the alkalies concentrated in certain types of igneous rocks? Why are many alkaline rocks so low in silica that feldspathoids form instead of feldspar? In many petrographic memoirs their authors have assumed that each alkaline comagmatic region is underlain by one or more reservoirs of magma which was rich in alkalies from "the foundation of the world." The visible eruptives are regarded as differentiates from such primeval segregations. A few writers have suggested the derivation of alkaline types from subalkaline magma by unusual processes of differentiation. No one has yet stated the conditions for this special differentiation. The succeeding pages bear an outline of a hypothesis intended in some degree to declare those conditions.

It will first be pointed out that no alkaline province can be described as free from subalkaline eruptives, especially those of basaltic or granitic types. Emphasis will be laid on the indisputable fact that the visible volume of all alkaline rock bodies is a very minute quantity as compared with the visible volume of subalkaline eruptive bodies. An inductive study shows that most alkaline rocks cut thick masses of limestones, dolomites, or other calcareous sediments. This fact suggests the hypothesis that the absorption of carbonate disturbs the chemical equilibrium of subalkaline magma in such manner that alkaline fractions are produced by differentiation. Most of the alkaline species are ascribed to the interaction of basaltic magma and limestone, but more acid magma is also sensitive to the solution of carbonate. The hypothesis explains the concentration of alkalies; the desilication shown by the crystallization of nephelite, leucite, corundum, etcetera; the extreme variability of alkaline bodies in mineralogical and chemical composition; the occurrence of such lime-bearing minerals as melilite, scapolite, wollastonite, melanite, etcetera, and such CO_2-bearing minerals as cancrinite and (primary) calcite. The difficult problem remains as to the physico-chemical reactions involved in the hypothesis. This paper is offered as an advertisement of the need for help from the physical chemists in giving a final explanation of the described geological facts of rock-association. The writer is indebted to Dr. H. S. Washington for helpful, though adverse, criticism.

Association of alkaline and subalkaline Rocks

In most alkaline provinces typical basalts, diabases, gabbros, diorite, andesite, (post-Archean) granite, or other common lime-alkali eruptives occur. From the character and distribution of the visible pre-Cambrian terrane, it is in the highest degree probable that its granite or greenstone exists at greater or less depth in some part of each alkaline province on the continental plateaus. This steady association is partly illustrated in the following table, which is far from being exhaustive even as regards the post-Archean eruptives. Very often alkaline and subalkaline types are represented in the same petrogenic cycle and province. A few examples may be extracted from the table. The gabbrö (with diorite) and diabase of Ascutney Mountain, Vermont, respectively open and close the eruptive series, which includes nordmarkite, paisanite, alkaline granite, camptonite, etcetera. The trachyte (acid phonolite) of Hawaii cuts, and is overflowed by, olivine basalt; the nephelite basalt of Oahu is interbedded with feldspar basalts. Feldspar basalts, with phonolites, compose Kerguelen, Fernando Noronha, Saint Helena, and other islands.

Whether associated alkaline and subalkaline rocks are products of one petrogenic cycle or have been erupted at long intervals of geological time, it is hard, if not impossible, to conceive that the alkaline bodies are offshoots from primeval reservoirs of foyaitic or other magma rich in soda and potash. This conception has held its place in petrology so long because of a systematic ignoring of the association described. The mind fails to grasp the intercrustal or subcrustal conditions which permit of the independent existence of initially alkaline and subalkaline magma chambers beneath the same, generally quite limited, areas of the earth's surface.

The conception is further at fault in not allowing for the comparatively minute volume of all the alkaline-rock bodies now known on the globe. The largest alkaline plutonic mass yet described is doubtless the nephelite syenite "laccolith" of the Kola Peninsula, with an estimated area of 1,600 square kilometers. The Kangerdluarsuk (Greenland) nephelite syenite covers 390 square kilometers. The Bancroft (Ontario) nephelite syenite covers about 25 square kilometers. These figures show the order of magnitude of the largest intrusive alkaline bodies. The alkaline extrusives are yet more numerous, but are generally of much smaller volume than any of these plutonic masses. The visible alkaline rock of an average locality covers but a few square kilometers, and its reasonably inferred volume is only a few cubic kilometers. All the visible alkaline rock of the world probably constitutes less than one per cent of the total visible igneous rock. The visible volume of the subalkaline Coast Range batholith of British Columbia and Alaska, covering at least 150,000 square kilometers, is doubtless much greater than that of all the world's known alkaline bodies put together.

There seems to be no reason to doubt that the size of the erupted bodies will be, on the average, in direct proportion to the size of the feeding magma chambers. If each chamber be a primeval alkaline reservoir, it has, accordingly, a very small size as compared with the known bodies of subalkaline granite or basalt. We are led to the deduction that relatively and absolutely small bodies of magma can conserve the heat appropriate to fluidity for scores of millions of years. Simple calculation and common sense show that this is an impossible supposition. If we turn on our tracks and deny the smallness of the alkaline-magma reservoirs we face a dilemma as clearly unacceptable to the field geologist.

Alkaline Rocks genetically connected with subalkaline Magmas

If subalkaline magma alone carries enough primary heat to be eruptible, it follows that alkaline magmas are either differentiates from subalkaline magma or syntectics,[2]—that is, solutions of foreign rock in subalkaline magma—or differentiates from such syntectics. For the first and third of these hypotheses the observed field association of the two rock groups, the relative volume of each group, and the chemical composition of the alkaline types are all more or less appropriate. We have seen that many subalkaline rocks actually carry more alkalies than some "alkaline" rocks. The extreme case of associated phonolite and basalt may be briefly discussed in preference. Average phonolite (calculated as water-free) carries about 9.0 per cent of soda and 5.3 per cent of potash. Average basalt (calculated as water-free) carries about 3.2 per cent of soda and 1.6 per

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[2] This word is adapted from Loewinson-Lessing. Compte Rendu, 7e session, Congrès géologique internationale, Saint Petersburg, 1899, p. 375.

cent of potash. If alkalies sufficient for one volume of phonolite were concentrated from twenty volumes of basalt, the residual magma would still have a composition little different from that of average basalt. The total volume of the known phonolites is surely not more than five per cent of the known volume of extruded basalt. Much slighter concentration of the alkalies from basalt would give the soda and potash appropriate to trachydolerite, tephrite, or basanite. These illustrations show that there is no violence done to the principle of magmatic differentiation in making it responsible for the derivation of alkaline rocks from subalkaline magmas. That derivation is further suggested by the numerous transitions observed between alkaline and subalkaline rocks.

Why is the eruptive sequence of subalkaline magmas ever broken? What is the cause of the concentration of their alkalies so that at certain times and places relatively small eruptions of alkaline magmas occur? The attempt to answer these questions is the central theme of this paper.

Association of alkaline Rocks with Limestones, Dolomites, and other calcareous Sediments

The following table gives a summary statement of the facts from which a general rule connecting alkaline igneous rocks and calcareous sediments may be deduced. With but few exceptions, if any, the magmas from which these eruptive rocks were derived cut limestone, dolomite, or other deposits containing notable proportions of carbonate.[3]

The sources of information used in making the table were reached chiefly through the lists of references published in the fourth edition of Rosenbusch's "Mikroskopische Physiographie der Massigen Gesteine." It was found that most of the petrographic papers give few facts regarding the formations cut by the alkaline eruptives. In many instances the more purely geological reports, memoirs, and maps have given valuable data on the subject. These additional references are usually the obvious ones; to keep this paper within a proper limit of size, they are not listed. The table is not complete, though it contains names of nearly all the important alkaline-rock districts now known on the globe.

In constructing the fourth column, it was often necessary to search for information as to the sedimentary terranes underlying the present land surface in the districts. Care was taken to assume limestone below the surface only when the facts pointed strongly in that direction. It was

[3] A remarkable illustration is found in the great nephelite syenite fields of eastern Ontario, where the foyaitic phase of the pre-Cambrian granitic batholiths is found at contacts with limestone. F. D. Adams and A. E. Barlow, Transactions of the Royal Society of Canada, third series, vol. 2, section 4, 1909, p. 8.

sometimes clear, too, that limestones were present in the roofs of alkaline intrusives of the stock or batholith order, and it is then legitimate to consider such limestone as subject to stoping and abyssal assimilation during intrusion. The blanks in the third column mean lack of information and not necessarily absence of subalkaline eruptions in the corresponding districts.

Table showing Field Associations of Alkaline and Subalkaline Eruptives and Calcareous Sediments

NORTH AMERICA

Region.	*Alkaline eruptives.*	*Associated subalkaline eruptives.*	*Carbonate rocks cut by alkaline eruptives.*
Bancroft, Ontario.	Nephelite syenite.	Anorthosite, granite, etcetera.	Grenville limestone.
Monteregian Hills, Quebec.	Theralite, essexite, pulaskite, nordmarkite, nephelite syenite, camptonite, bostonite, tinguaite, sölvsbergite, fourchite, monchiquite, alnöite.	Gabbro, diabase, etcetera.	Chazy, Trenton, and Devonian limestones. Pre-Cambrian limestone. ?
Ottawa Valley, Quebec.	Shonkinite.	Granite, diabase, pyroxenite, etcetera.	?
Pooh-bah Lake, Ontario.	Malignite.	Diabase, granite, etcetera.	?
Port Coldwell, Ontario.	Nephelite syenite.	Gabbro.	?
Heron Bay, Ontario.	Heronite.	Diabase.	?
North-central Wisconsin.	Nephelite syenite, etcetera.	Gabbro, diorite, granite, etcetera	? Calcareous graywacke, chert, shale, and slate in older terrane.
Southwest Alaska.	Leucite phonolite.	Granodiorite, etcetera.	Paleozoic limestones beneath Jurassic series.

Table showing Field Associations of Alkaline and Subalkaline Eruptives—Continued.

Region.	*Alkaline eruptives.*	*Associated subalkaline eruptives.*	*Carbonate rocks cut by alkaline eruptives.*
Ice River, British Columbia.	Nephelite syenite, ijolite, cancrinite syenite, urtite, tinguaite.		Limestones and dolomites of Beltian, Cambrian, Devonian (?), and Carboniferous (?).
Kruger Mountain, British Columbia.	Nephelite syenite, malignite.	Granodiorite, gabbro, andesites, peridotites, etcetera.	Paleozoic limestone (?).
Kettle River, British Columbia.	Rhomb porphyry, analcitic rhomb-porphyry, alkaline trachyte.	Basalt, andesites, gabbros, etcetera.	Paleozoic limestone (?).
Rossland, British Columbia.	Monzonite, latites, missourite.	Basalts, andesites, gabbros, etcetera.	Carboniferous limestone.
Salmon River, British Columbia.	Monzonite.	Granite, basalt, andesites, etcetera.	Thick Paleozoic limestones.
Bearpaw Mountains, Montana.	Leucite basalt, mica-trachyte, shonkinite, monzonite, augite syenite, nephelite basalt, leucitite, tinguaites.		Paleozoic and Mesozoic limestones and dolomites.
Highwood Mountains, Montana.	Syenites, monzonite, shonkinite, fergusite, missourite, trachy-andesite, gautëite, leucite shonkinite, analcite basalt, minette.	Basalt, diorite, granite porphyry, granite, etcetera.	Paleozoic and Mesozoic limestones and dolomites.
Judith Mountains, Montana.	Tinguaites (augite phonolites).	Diorite and granite, porphyries, etcetera	Ditto.

Table showing Field Associations of Alkaline and Subalkaline Eruptives—Continued.

Region.	*Alkaline eruptivvs.*	*Associated subalkaline eruptives.*	*Carbonate rocks cut by alkaline eruptives.*
Little Belt Mountains, Montana.	Syenite, monzonite, shonkinite, analcite basalts, vogesites, minettes.	Basalt, diorite, and granite.	Ditto; also some Beltian (Belt terrane) limestones.
Castle Mountains, Montana.	Theralite, acmite trachyte.	Ditto.	Ditto.
Crazy Mountains, Montana.	Theralite, acmite trachyte.	Diorite, granite, etcetera.	Ditto.
Cœur d'Alene district, Idaho.	Monzonites.	Diabase.	Limestone, dolomite, and calcareous argillites of Belt terrane.
Goldfield, Nevada.	Monzonite porphyry and latite.	Basalt, andesite, rhyolite, etcetera.	Cambrian limestone and calcareous shale.
Tintic, Utah.	Monzonite.		Carboniferous limestones.
Yellowstone Park.	Monzonite, syenite, absarokite, shoshonite.	Liparite, granite, diorite, etcetera.	Paleozoic limestones.
Sundance Quadrangle, Wyoming-South Dakota.	Monzonite, leucite porphyry, nephelite syenite, bostonite, ijolite, nephelinite, fourchite, camptonite, vogesite, pyroxenite.		Paleozoic limestones.
Aladdin Quadrangle, Wyoming-South Dakota - Montana.	Suite including some types of Sundance list.		Ditto.
Leucite Hills, Wyoming.	Wyomingite, orendite, madupite.	Granite.	Paleozoic and Mesozoic limestones.

Table showing Field Associations of Alkaline and Subalkaline Eruptives—Continued.

Region.	*Alkaline eruptives.*	*Associated subalkaline eruptives.*	*Carbonate rocks cut by alkaline eruptives.*
Black Hills, South Dakota.	Phonolite, grorudite.	Diorite, liparite.	Ditto.
Denver Basin, Colorado.	Trachydolerite.		Mesozoic limestones of four horizons.
Rico District, Colorado.	Monzonite.		Paleozoic limestones
La Plata Quadrangle, Colorado.	Monzonite.		Paleozoic and Jurassic limestones, calcareous sandstones, etcetera.
Telluride Quadrangle, Colorado.	Monzonite.		Ditto.
Georgetown Quadrangle, Colorado.	Alkali syenite porphyry, latite, bostonite, etcetera.	Diorite, granite, etcetera.	Pre-Cambrian limestone.
Cripple Creek District, Colorado.	Phonolite, latite-phonolite, syenite, trachydolerite, vogesite, monchiquite.	Granite, olivine-syenite, anorthosite, diabase	?
Spanish Peaks, Colorado.	Monzonite porphyry.		Mesozoic and probably Paleozoic limestones and calcareous shales.
Magnet Cove, Arkansas.	Nephelite syenite, ijolite, shonkinite, leucite porphyry, tinguaite, monchiquite, jacupirangite.		Paleozoic magnesian limestones.
Walsenburg Quadrangle, New Mexico.	Monzonite porphyry.		Ditto.

Table showing Field Associations of Alkaline and Subalkaline Eruptives—Continued.

Region.	*Alkaline eruptives.*	*Associated subalkaline eruptives.*	*Carbonate rocks cut by alkaline eruptives.*
Pilot Knob, Texas.	Nephelite basalt.		Cretaceous (and older ?) limestones.
Apache Mountains, Texas.	Nephelite syenite, other syenites, tinguaite, bostonite, paisanite, phonolite.		Paleozoic and Mesozoic limestones.
Uvalde County, Texas.	Melilite - nephelite basalt, nephelite basanite, phonolite, nephelite basalt, limburgite.	Plagioclase basalt.	Mesozoic (and older ?) limestones and marls.
Big Trees Quadrangle, California.	Latites.	Granodiorite, andesites, basalt, etcetera.	Paleozoic limestones and clay slates.
Mother Lode District, California.	Latites.	Ditto.	Ditto.
Point Sal, California.	Teschenite.		Tertiary limestones and clays; Cretaceous shales.
San Luis Obispo County, California.	Analcite diabase.		Ditto.
Beemerville, New Jersey.	Nephelite syenite.	Diabase, etcetera.	Lower Paleozoic dolomitic limestones. (Also pre-Cambrian limestones ?)
Brookville, New Jersey.	Nephelite syenite.	Diabase.	Pre-Cambrian limestone adjacent.
Adirondack Mountains, New York.	Alkaline syenite.	Anorthosite, granite, etcetera.	Grenville limestone.

Table showing Field Associations of Alkaline and Subalkaline Eruptives—Continued.

Region.	*Alkaline eruptives.*	*Associated subalkaline eruptives.*	*Carbonate rocks cut by alkaline eruptives.*
Essex County, Massachusetts.	Foyaite, essexite, tinguaite, pulaskite, akerite, sölvsbergite, nordmarkite, keratophyre, paisanite, alkaline granites.	Diabase, diorite, gabbro, etcetera.	Lower Cambrian limestones and calcareous argillite. (Also younger and older limestones ?)
Red Hill, New Hampshire.	Foyaite, umptekite, paisanite, bostonite, camptonite, etcetera.	Granites, etcetera.	? (Paleozoic limestones in roof now eroded away ?).
Mount Ascutney, Vermont.	Alkaline syenites, etcetera.	Diabase, diorite, gabbro.	Marbles and "Calciferous Mica Schist."
Litchfield, Maine.	Nephelite syenite, bearing much cancrinite.		? not in place. Syenite.
San José District, Mexico.	Nephelite syenite, camptonite.	Basalt, andesite.	Cretaceous limestone.
Costa Rica.	Theralite.		Tertiary (and older ?) limestones.
SOUTH AMERICA			
Sao Paulo, Brazil.	Nephelinite, teschenite, vogesite, jacupirangite, foyaite, augite syenite, laurvikite, augitite, limburgite.	Diabase, diorite.	Paleozoic limestone in clay-slates, etcetera. (Also pre-Cambrian limestones ?)
Caldas, etcetera, Brazil.	Foyaite, phonolite, leucitophyre.		?
Paraguay.	Phonolite, limburgite.		?
Salta Province, Argentine.	Trachydolerite, essexite.		?
San Juan Province, Argentine.	Nephelite basalt, essexite, trachyte-tephrite, limburgite.	Feldspar basalt, andesites, dacite, etcetera.	Paleozoic (?) and Jurassic limestones.

EUROPE

Table showing Field Associations of Alkaline and Subalkaline Eruptives—Continued.

Region.	*Alkaline eruptives.*	*Associated subalkaline eruptives.*	*Carbonate rocks cut by alkaline eruptives.*
Loch Borolan, Scotland.	Foyaite, pulaskite, borolanite.		Lower Paleozoic dolomites and limestones.
Eildon and Garlton Hills, Scotland.	Phonolite-trachyte, phonolite.		?
Pouzac, Pyrenees.	Nephelite syenite, bostonite, etcetera.	Diabase.	Jurassic and Cretaceous limestones and calcareous breccias.
Velay, France.	Phonolite, trachyte.	Basalt, andesite.	Tertiary marls, limestone, with gypseous beds.
Fortuna, Spain.	Fortunite, jumillite, trachyte.		Tertiary marls, Cretaceous limestones. (Older limestones?)
Catalonia, Spain.	Nephelite basanite, limburgite.	Olivine basalt.	Tertiary and older limestones.
Serra de Monchique, Portugal.	Nephelite syenite, pulaskite, bostonite, tinguaites, monchiquite, camptonite.	Diabase.	Pre-Culm limestones.
Cezimba, Fonte da Bica, etcetera, Portugal.	Teschenite.	Diabase.	Cretaceous and older limestones.
Italian districts as under: Vulsinian, Ciminian, Sabatinian, Latian, Hernican, Auruncan, Campanian, Vesbian, Phlegrean, Mount Vulture, Tuscan, Venetian, Apulian (named by H. S. Washington).	Trachytes, leucite phonolites, leucite trachytes, leucite tephrites, latites, leucitites, leucite basanites, vulsinites, melilitic leucitites, etcetera.		Mesozoic and Tertiary limestones and dolomites. (Also Paleozoic limestones?)

Table showing Field Associations of Alkaline and Subalkaline Eruptives—Continued.

Region.	*Alkaline eruptives.*	*Associated subalkaline eruptives.*	*Carbonate rocks cut by alkaline eruptives.*
Predazzo, Tyrol.	Nephelite syenite, essexite, shonkinite, theralite, monzonite, tinguaite, camptonite, monchiquite, etcetera.	Melaphyre, etcetera.	Triassic dolomite. (Also older limestones?)
Monzoni, Tyrol.	Monzonite, essexite, alkaline syenites, tinguaites, etcetera.		Ditto.
Kaiserstuhl, Baden.	Phonolite, nephelite basalt, limburgite, leucite basalt, tephrite, leucite, phonolite, etcetera.		Mesozoic and Tertiary limestones, dolomites, and marls.
Haardt Mountains, Elsass; Mainz basin, etcetera.	Limburgite.		Muschelkalk and older and younger limestones.
Katzenbuckel, Baden.	Nephelite basalt, shonkinite, theralite, etcetera.		Mesozoic limestones and dolomites.
Hegau, Baden.	Nephelite basalt, melilite-nephelite basalt, melilite basalt, phonolite.	Feldspar basalt.	Ditto.
Suabian Alp.	Melilite basalt.		Ditto.
Siebengebirge.	Essexite, trachydolerite, monchiquite, trachyte, etcetera.		Devonian calcareous graywacke and older sediments.
Eifel.	Leucite basalt, nephelite basalt (bearing melilite), phonolite.		Ditto.
Vordereifel.	Ditto.		Ditto.

Table showing Field Associations of Alkaline and Subalkaline Eruptives—Continued.

Region.	*Alkaline eruptives.*	*Associated subalkaline eruptives.*	*Carbonate rocks cut by alkaline eruptives.*
Westerwald.	Phonolite.		Devonian limestone adjacent.
Weser-Werra-Fulda District.	Nephelite basalt, leucite basalt, melilitic nephelite basalts.	Feldspar basalt.	Mesozoic limestones and marls and Paleozoic calcareous sediments.
Rhön.	Phonolite, trachyte, nephelite basalt (often leucititic), limburgites, basanites.	Feldspar basalt.	Ditto.
Vogelsberg.	Nephelite basalt, phonolite, trachyte.	Anamesite, basalt.	Ditto.
Duppau Hills, Bohemia.	Phonolite, leucite basalt, leucitite, leucite tephrite, leucite basanite, nephelite basalt, nephelinite, nephelite tephrite, limburgite, augitite, nephelite syenite, augite syenite, theralite.	Feldspar basalt, andesite.	Tertiary marls and calcareous tuffs.
Mittelgebirge, Bohemia.	Phonolite, tephrite, essexite, sodalite syenite, trachyte, nephelite basalt, limburgite, melilite basalt.	Feldspar basalt.	Mesozoic and Paleozoic limestones and marls.
Steiermark, Austria.	Nephelite basanite, nephelinite, nep elite basalt.		Tertiary, Mesozoic (and older?) limestones and marls.
Ditro, Hungary.	Nephelite syenite (many phases)		Limestones in phyllitic terrane. (Also younger limestones ?)

Table showing Field Associations of Alkaline and Subalkaline Eruptives—Continued.

Region.	*Alkaline eruptives.*	*Associated subalkaline eruptives.*	*Carbonate rocks cut by alkaline eruptives.*
Azof, Russia.	Mariupolite, orthophyre, grorudite, pyroxenite, etcetera.	Basalt, diabase.	? Paleozoic (Devonian and Carboniferous) limestones?
Miask and Kussa, Russia.	Nephelite syenite, cancrinite syenite, corundum syenite.	Granite.	Crystalline limestone adjacent.
Kuusano Parish, Finland.	Nephelite syenite, ijolite.		?
Kuolajärvi, Finland.	Cancrinite syenite.		?
Kola Peninsula, Russia.	Nephelite syenite, urtite, lujaurite, umptekite, chibinite, etcetera.	Augite porphyrite, granites.	Devonian (?) marly clay-slates. (Also limestone?)
Alnö, Sweden.	Foyaite, ijolite, jacupir angitic phases, bostonite, alnöite, etcetera.	Granite.	Crystalline limestone.
Elfdalen, Sweden.	Cancrinite tinguaite.	Quartz porphyry, augite porphyrite, etcetera.	Paleozoic limestones?
Gran, Norway.	Bostonite, camptonite.	"Olivine-gabbro-diabases," pyroxenite, hornblendite.	Paleozoic limestones, including Étages 1 to 3.
Christiania, Norway.	Essexites, akerites, laurvikites, monzonites, laurdalite, pulaskite, nordmarkite, ekerite, camptonite, rhomb-porphyry, etcetera.	Granite, diabase, etcetera.	Paleozoic limestones (and argillites).

Table showing Field Associations of Alkaline and Subalkaline Eruptives—Continued.

AFRICA.

Region.	*Alkaline eruptives.*	*Associated subalkaline eruptives.*	*Carbonate rocks cut by alkaline eruptives.*
Kamerun, Africa.	Monzonite, keratophyre, bostonite, camptonite, vogesite, leucitite, etcetera.	Diabase, diorite, etcetera.	Cretaceous (and older?) limestones.
Niger-Benué area, West Africa.	Foyaite.		Limestone of unknown age.
Ahaggar, Central Africa.	Phonolite.	Basalt, granite.	?
Aïr, Central Africa.	Phonolite, alkaline trachyte.	Granite, rhyolite.	Silurian limestones; (Cretaceous marls ?; other limestones?)
Great Rift Valley, East Africa.	Phonolites, comendites, trachytes, kenites, nephelinites (bearing melilite), borolanite, nephelite basalt, limburgite, tephrite, nephelite basanite, leucite basanite.	Olivine basalt.	? Crystalline limestones of gneissic plateau; calcareous sandstone, conglomerate and shales of Paleozoic?
Abyssinia.	Phonolites, tinguaites, grorudite, paisanite, sölvsbergite, etcetera.	Olivine basalt, diabase, gabbro, diorite, etcetera.	Thick crystalline limestones and dolomites in gneissic plateau; also Jurassic and younger limestones.
Bushveld, South Africa.	Nephelite syenite, monchiquite, camptonite, bostonite, etcetera.	Norite, gabbro, granite, etcetera.	The Great Dolomite.
Marico, Transvaal.	Nephelite syenites.	Norite, gabbro.	Ditto.

Table showing Field Associations of Alkaline and Subalkaline Eruptives—Continued.

ASIA.

Region.	*Alkaline eruptives.*	*Associated subalkaline eruptives.*	*Carbonate rocks cut by alkaline eruptives.*
Aden peninsula.	Phonolite, trachytes.		Cretaceous limestone? Older limestones?
Northern Syria.	Nephelite basanite, limburgite.	Feldspar basalt.	Cretaceous limestones.
Kula, Asia Minor.	Kulaite (trachydolerite), leucite kulaite.	Diabase, diorite, etcetera.	Tertiary (and older?) limestones.
Madras, India.	Nephelite syenites, augite syenite, corundum syenite.		? Crystalline limestone in schistose terrane.
Mount Girnar, India.	Nephelite syenite, monchiquite.	Olivine gabbro, diorite.	?
Southern China.	Nephelite syenites.		? Paleozoic (Devonian) calcareous terrane "d'une immense étendue."
Jenisseisk (P. Tunguska), Siberia.	Leucite syenite porphyry.	Olivine-augite-plagioclase rock.	Silurian limestone.
"Ostsibirien" (Jenissiesk).	Teschenite.	Melaphyre.	Limestones and dolomite.

AUSTRALIA.

Warrumbungle Mountains, New South Wales.	Phonolite, trachyte, pseudoleucite phonolite, trachydolerite, comendite, melilite basalt (bearing corundum).		Calcareous shale of Triassic; Paleozoic limestones beneath the Triassic?

Table showing Field Associations of Alkaline and Subalkaline Eruptives—Continued.

Region.	*Alkaline eruptives.*	*Associated subalkaline eruptives.*	*Carbonate rocks cut by alkaline eruptives.*
Nandewar Mountains, New South Wales.	Akerite, nephelite syenite, bostonite, trachyte.	Basalt, rhyolite.	? Paleozoic limestones and calcareous sandstones, shales, etcetera ?
New South Wales province in general (eight districts).	List same as for Warrumbungle and Nandewar Mountains; also leucite basalt, etcetera.	Basalt, granites, dacite, andesites, etcetera.	Permo - Carboniferous, Devonian, and Silurian limestones and calcareous shales. Pre-Cambrian limestone ?
Queensland (five districts).	Monzonite, keratophyre, trachytes, comendite, etcetera.	Ditto.	? Palezoic limestones ?
ANTARCTICA.			
Track of the "Discovery" party; mainland, Ross Archipelago, etcetera.	Kenite, trachyte, leucitekenite, phonolite, trachydolerite, limburgite, camptonite, etcetera.	Basalt, granite, etcetera.	? Thick crystalline limestones of gneissic terrane ?
ISLANDS.			
Possession Island, Antarctic.	Phonolite.	Basalt.	?
Dunedin, New Zealand.	Foyaite, trachydolerite, teschenite, trachyte, kaiwekite, phonolite, tinguaites, leucitophyre, nephelite basanite, trachytes, melilite basanite.	Feldspar basalt, dolerite, diorite.	Tertiary limestone and calcareous sandstone. (Older limestones and marls ?)

Table showing Field Associations of Alkaline and Subalkaline Eruptives—Continued.

Region.	*Alkaline eruptives.*	*Associated subalkaline eruptives.*	*Carbonate rocks cut by alkaline eruptives.*
Tasmania, Port Cygnet, etcetera.	Nephelite syenites, augite syenite, essexite, jacupirangite nephelinite, tinguaite, nephelite, basalt, melilite-nephelite basalt, limburgite, etcetera.	Diabase.	Paleozoic limestones.
Timor.	Foyaite.	Diabase, andesite.	Tertiary and Carboniferous limestones.
Java.	Tephrite, leucite basalt, leucitite.	Feldspar basalt, andesite.	? Limestone in older terrane (Verbeek and Fennema).
Viti Archipelago.	Foyaite.	Basalt, gabbro, diabase, granite, etcetera.	? Crystalline limestone in island basement. Younger limestones ?
Savaii, Samoa.	Trachydolerite.	Olivine basalt.	?
Tahiti.	Nephelite syenite, monzonite, tinguaite, monchiquite, nephelinitic gabbro.	Basalt, gabbro.	?
Hawaii.	Phonolitic trachyte.	Olivine basalt, augite andesite.	? Ancient coral reefs, oozes, etcetera.
Maui.	Melilite - nephelite basalt.	Ditto.	?
Oahu.	Nephelite basalt, melilite-nephelite basalt.	Ditto.	?

Table showing Field Associations of Alkaline and Subalkaline Eruptives—Continued.

Region.	*Alkaline eruptives.*	*Associated subalkaline eruptives.*	*Carbonate rocks cut by alkaline eruptives.*
Madagascar.	Nephelite syenite, nephelite basalt, phonolite, trachyte, limburgite, camptonite, melilite basalt, laurvikite, monzonite, augitite, essexite.	Diabase, feldspar basalt, gabbro.	Jurassic limestones and marls. (Older limestones?)
Trinidad, South Atlantic.	Phonolite, nephelinite, limburgite.		? Coral reefs?
Heard.	Nephelite basalt, limburgite.	Feldspar basalt.	?
Kerguelen.	Phonolite, trachyte, limburgite.	Feldspar basalt.	? (Roth found dolomite here.)
Nightingale.	Phonolite.	Andesite.	?
Fernando Noronha.	Phonolite.	Feldspar basalt.	?
Cabo Frio (Brazil).	Foyaite, pulaskite, essexite, tinguaite, monchiquite.		?
Saint Helena.	Phonolite.	Feldspar basalt, olivine basalt.	?
Ascension.	Alkaline trachyte.	Ditto.	?
São Thomé.	Phonolite, trachyte	Feldspar basalt, andesite.	?
Los Islands (Africa).	Nephelite syenite.		?

Table showing Field Associations of Alkaline and Subalkaline Eruptives—Continued.

Region.	*Alkaline eruptives.*	*Associated subalkaline eruptives.*	*Carbonate rocks cut by alkaline eruptives.*
Canary Islands.	Phonolite, trachydolerite, basanite, nephelinite, limburgite, tephrite, essexite, nephelite syenite, monzonite, camptonite, bostonite, gautëite, limburgite, nordmarkite, pulaskite, akerite.	Feldspar basalt.	? Mesozoic and Paleozoic limestones beneath volcanoes? Limestone on Fuerteventura. (Continuation of Atlas Mountains limestone formations?)
Cape Verde Islands.	Foyaite, syenite, phonolite, leucitite, tephrite, basanite, nephelinite, nephelite basalt, limburgite, etcetera.	Diabase, basalt, diorite, etcetera	? Limestones of Mayo, S. Thiago, and Praya islands?
Greenland.	Foyaite, sodalite syenite, lujaurite, etcetera.	Diorite, granite.	? (Pre-Cambrian limestones?)
Columbretes (Mediterranean).	Phonolite, trachyte.	Olivine basalt.	?
Monte Ferru, Sardinia.	Phonolite, trachydolerite, leucite basanite, leucite basalt.		Tertiary limestones and marls (older limestones?).
Pantelleria.	Phonolite, trachydolerite.	Feldspar basalt, olivine basalt of Ferdinandea Island (1831).	? (Tertiary and Mesozoic limestones?)
Lipari Islands.	Leucite basanite, trachydolerite, etcetera.	Basalt, liparite.	? (Tertiary and Mesozoic limestones?)

For 107 of the 155 districts tabulated the rule connecting alkaline eruptives and carbonate rocks is quite clear. In many of the remaining cases, including most of the oceanic islands, full information as to the nature of the formations invaded by the magmas could not be found in the literature or in geological maps. The phonolitic intrusives and lavas of the Cripple Creek district, Colorado, cut pre-Cambrian granites, and there is little probability that their magma could have made contact with any limestone overlying those granites. The alkaline rocks of Red Hill, New Hampshire, cut orthogneiss which seems to be similarly barren of carbonate beds, but it is possible that limestones occurred in the roof of the Red Hill stock; or it is possible that both the Red Hill and Cripple Creek granites traversed by the alkaline magmas had incorporated (stoped down) large masses of limestone during the earlier, batholithic intrusion, and that these limestones were cut by the foyaitic magmas. That this speculation is not entirely fantastic is shown by the fact that the deeper mine workings of the Cripple Creek district are seriously affected by abundant emanations of carbonic acid gas; that gas comes from below or from the volcanic rocks in which the levels are run and the shafts sunk; or, finally, it is possible that the Cripple Creek, Red Hill, and some other alkaline magmas have nowhere made contact with carbonate rocks, though those magmas were for some special reason unusually rich in juvenile carbon dioxide.

These exceptional cases suggest the hypothesis that it is the presence of carbon dioxide rather than of dissolved carbonate in subalkaline magma, which is the principal condition for the differentiation of fractions high in alkalies. The following discussion will, however, refer chiefly to the effect of the assimilation of limestone and dolomite, with their combined carbon dioxide, by subalkaline magma.

Effects of the Solution of Carbonates in subalkaline Magma

Needless to say, the experimental data are yet insufficient for a complete physico-chemical analysis of this subject. What follows is but a series of the more manifest suggestions or inferences derived from general studies of silicate melts and of the solid rocks. Incomplete as the deductions may be, they all point toward the one conclusion—that subalkaline magma must suffer such chemical modification by the assimilation of carbonates as will lead to fractions which are either abnormally rich in the alkalies or are so far desilicated as to yield, by crystallization, feldspathoids instead of feldspars. The various points will be very briefly stated, for it is the writer's purpose to draw to the main hypothesis the attention of geologists and others who, by training, are better qualified to discuss the physico-chemical processes involved. A few illustrative points may be noted, with the commonest lava, basalt, taken as a type of the subalkaline magma.

1. Limestone or dolomite is a flux for basalt. The solution of a small proportion of either carbonate promotes fluidity. If there be any tendency toward the separation (by gravity) of leucocratic and melanocratic elements, this differentiation is directly aided by increased fluidity. Square Butte and Shonkin Sag prove very clearly that there is such tendency in magma (leucite basalt, cutting thick limestones) which, in chemical composition, differs relatively little from feldspar basalt.[4]

The facts concerning many other igneous bodies teach the same truth, namely, that gravitative differentiation, with concentration of alkalies in the upper part of magma chambers, is a normal process in those magmas which retain considerable fluidity near the crystallization temperatures of the femic and "cafemic" (calcium-iron-magnesium) components. This result is evidently brought about by fluxing.

2. The solution of limestone in basalt is accompanied by the dissociation of at least part of the carbonate. The lime binds several times its own weight of silica, with which iron oxides and magnesia may be also combined, forming pyroxene. The introduction of more of the ion, CaO, already present in the magmatic solution, promotes the precipitation of augite, anorthite, and other lime-bearing crystals or liquid phases.[5] An inoculation of the solution is evidently produced by the exotic carbonate.

3. The sinking of the femic and cafemic constituents (in solid or liquid phases) leaves the upper, residual part of the magma richer in alkalies than the original basalt. So far as the foreign lime has bound silica and carried it down in the sunken constituents, the residual magma is desilicated as compared with the original basalt. If the desilication is sufficient, nephelite forms instead of plagioclase. If augite is formed by the interaction of the foreign rock, a considerable desilication is possible, for the lime then binds about 2.5 times its own weight of silica. The formation and sinking of calcic, cafemic, and femic constituents leave the residual solution rich in alumina.

4. The carbon dioxide freed from the lime of the foreign rock must have a profoundly disturbing effect on the chemical equilibrium of the basalt. What that effect is can not be told until new, complete experi-

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[4] L. V. Pirsson: Petrography and geology of the igneous rocks of the Highwood Mountains, Montana, Bulletin 237, U. S. Geological Survey, 1905.

[5] Similarly, if barium chloride is added to a saturated solution of barium sulphate, almost all of the barium sulphate is precipitated. See J. H. L. Vogt: Tschermak's Mineralogische Mitteilungen, vol. 27, 1908, p. 134.

ments have been made on such a solution. It appears possible that, in the absence of uncombined silica, the carbon dioxide would form compounds with the alkalies. These familiar fluxes would tend to rise toward the top of the magma chamber. A given amount of the acid would transfer a larger amount of either soda or potash. With falling temperature and at the pressures appropriate to the upper part of the chamber, the carbon dioxide would be slowly replaced by silica and expelled through the roof of the chamber. On the other hand, the reaction may be much more complicated than that suggested, and, in fact, it is likely that the alkalies often move upward in the form of aluminosilicate. The problem illustrates the darkness yet shrouding the operations of the "agents minéralisateurs."

That there is an actual transfer of one or both alkalies is shown in such examples as basanite, leucite basalt, and nephelinite.* The alkaline contents of these rocks can not be explained as features of magmas which are residual after the settling out of femic and cafemic constituents from normal basalt.

Without speculating further as to the nature of the physico-chemical changes, we may note that both acid and basic elements of dissolved carbonates cooperate in concentrating alkalies in the upper part of a column of basalt. A similar argument and conclusion may be derived for other subalkaline magmas.

Additional Evidences favoring the Hypothesis

Besides the facts of field association and the high probability of appropriate physico-chemical reactions, there are a number of important considerations favoring the general thesis of this paper.

Many special pyrogenetic minerals, more or less peculiar to the alkaline rocks, herewith find that explanation which is often so difficult on the supposition that these rocks have crystallized from primary magma. The list includes:

First. Minerals with carbon dioxide as an essential component: calcite and cancrinite of nephelite syenite, etcetera.

Second. Minerals showing desilication of normal subalkaline magmas: nephelite, leucite, muscovite (? in part ?), sodalite, haüynite, analcite, corundum, spinel.

Third. Minerals formed through the presence of excess lime: melilite, scapolite, wollastonite, garnet, titanite (in part), calcite, anorthoclase (in part ?), perovskite.

* See table of average compositions of these and other types in Proceedings American Academy of Arts and Sciences, vol. 45, 1910, pp. 228-229.

Fourth. Mineral derived from organic matter in limestone (?): graphite in some nephelite syenites.

In Clarke's "Data of Geochemistry" a large number of experiments on the origin of these minerals are described in abstract from the writings of many observers.[6] These artificial reproductions show instructive analogies to the processes which doubtless affect the crystallization of a limestone-basalt syntectic. Particular reference may be made to the syntheses of cancrinite, nephelite, leucite, analcite, haüynite, corundum, melilite, scapolite (meionite), wollastonite, garnet, titanite, and graphite.

The metamorphism of limestones and dolomites by intrusive masses involves chemical changes which are somewhat similar to those taking place in the syntectic of limestone and subalkaline magma. The production of garnet rock, epidote rock, diopside rock, or amphibolite in contact aureoles implies some desilication of the magma. It loses iron oxides as well. The alkalies are normally transferred into the contact rock to small degree, and are thus left concentrated in the magma.

A few relevant experiments may be noted. Limestone flux precipitates magnetite from furnace slag. Similarly, diopside and wollastonite molecules are, after the lapse of sufficient time and at moderate superheat, segregated in special abundance at the bottom of glass furnaces, the overlying layers of the melt being richer in the alkaline silicate. On the other hand, the writer is not acquainted with any case where the positive concentration of alkalies in a subalkaline magma through the action of limestone fluxing has been carefully studied in laboratory or commercial plant.

Possible Objections to the Hypothesis

At present this suggestion as to the origin of the alkaline rocks obviously suffers from incompleteness on the physico-chemical side. However, enough is already known to assure any future investigator that he will obtain valuable results on fashioning his experiments along the lines of the present hypothesis; the geological facts seem to show that those results will favor the general idea of limestone control, or at least carbon dioxide control, in the development of alkaline rock magmas.

The hypothesis as above outlined is a special case in the general syntectic-differentiation theory of igneous rocks and may prompt the objections which have been directed against the theory.[7] There are plenty of field examples showing that the magmatic heat of basalt is ample to fuse

[6] F. W. Clarke: Bulletin 330, U. S. Geological Survey, 1908.
[7] R. A. Daly: American Journal of Science, vol. 26, 1908, p. 49.

so refractory a rock as gneiss or granite. The temperature of the active Kilauean vent is at least 1200° centigrade. If the fusion or solution of gneiss takes place at any such temperature, we must believe that fluxing carbonate can enter into solution with the molten basalts of nature. It appears that any subalkaline magma would be similarly fluxed. A few rock types such as melilite basalt probably represent syntectics which have differentiated only slightly, but, in general, differentiation will be specially active in limestone syntectics. Typical hybrid rocks are, therefore, not to be expected in most districts. On the contrary, differentiates poor in lime are the result of the absorption of limestone by subalkaline magmas. Such a differentiate is found near the top of the magma chambers. The known structural relations of nephelite syenites and of phonolites are appropriate to this position of the extreme polar differentiate in intrusive mass or lava column. If magmatic stoping of limestone takes place, the ensuing assimilation is abyssal, and the actual syntectic solution or rock may never be accessible to direct observation. Finally, it must be remembered that most stock and batholith contacts have been established after molar-contact assimilation has become almost impossible in the already much cooled magma. The question of magmatic assimilation can never be so easily settled as by a mere inspection of main contacts or of xenolithic inclusions. To deny the efficiency of magmatic assimilation on such evidence is scarcely a scientific judgment.

A conceivable objection to the hypothesis is that limestones and other calcareous sediments are very generally distributed over the earth's surface, and accordingly the observed association of alkaline rocks and the sediments is accidental and without significance. A final reply to this objection would involve a full discussion of the field relations of the subalkaline rocks. This colossal task need not be undertaken, for a partial review of the subalkaline rock occurrences must make it clear to every one that very many, perhaps most, of these bodies have not contacted with limestone during eruption.

Again, the hypothesis must take account of a considerable number of cases where subalkaline rocks now make contact with masses of calcareous sediment and are not accompanied by rock types which are evidently alkaline by our definition of the term. This is true of many batholiths which have absorbed much silicious rock as well as limestone. The net result has been to give an acid syntectic and then quartzose or feldspathic differentiates at the batholithic roofs. On the other hand, the absorbed sediments are often so great in amount as to give syenite instead of granite. If the limestone is relatively abundant, the syenite may be of nordmarkitic, pulaskitic, or other alkaline type. In the rare cases where limestone is extremely voluminous as compared with the acid rocks invaded, a granitic batholith may be locally desilicated and differentiated so as to produce nephelite syenites. Illustrations are seen in the great batholiths of eastern Ontario, as described by Adams, Barlow, Coleman, and others.[8] Many other bodies, smaller than batholiths, have no alkaline differentiates. Most of them were clearly too small to have assimilated any notable quantity of foreign rock, even of limestone. Some bodies have failed to assimilate because of their low temperatures. Where thermal and other conditions are necessarily so variable, *each case has evidently to be studied by itself* before its bearing on our general hypothesis is visible.

Alkaline Rocks not associated with calcareous Sediments

It would not be surprising if in future time it is demonstrated that some of the so-called alkaline rocks were evolved under conditions *essentially different* from those controlling the formation of such types as phonolite, nephelite syenite, theralite, etcetera. For example, many alkaline granites which cut granodiorite masses are most probably salic differentiates of the granodioritic magmas. In many of these cases the differentiation seems to be a result of the spontaneous splitting of the magmas rather than an effect of their absorption of foreign material. The splitting may have been assisted by the concentration of gases in part of the batholithic chamber, but those gases may *be juvenile and not "resurgent."*[9]

An analogous cause for the differentiation of phonolite has been suggested in the case of the Cripple Creek district. The alkaline masses of that region occur on the top of the great dome which, in Tertiary time, was upwarped to form the Front Range of Colorado. The development of such a dome must mean an extensive inflow of the plastic material on which the deformed granite rests. The disturbance might readily be conceived to lead to the concentration of juvenile gases, including carbon dioxide, beneath the domed granitic shell. A late Tertiary abyssal injection of basaltic magma would naturally carry much of this accumulated gas; the differentiation of this magma might give the latite-phonolite,

[8] F. D. Adams and A. E. Barlow: Transactions of the Royal Society of Canada, third series, vol. 2, section 4, 1909, p. 8. A. P. Coleman: Journal of Geology, vol. 7, 1899, p. 437.

[9] The writer uses "resurgent" as a technical term to designate those volatile substances which, as constituents of sedimentary rocks assimilated by magma, have been given off from the secondary, syntectic magma. Juvenile gases, on the other hand, are those emanating for the first time from the earth's interior. See American Journal of Science, vol. 26, 1908, p. 48.

phonolite, and nephelite syenite of Cripple Creek. The alkaline fractions of the differentiation were, on this view, segregated through the influence of the juvenile gas in the same manner as that postulated when the carbon dioxide of absorbed limestone segregates the alkaline elements in basalt. Similarly, the phonolites and allied types of many volcanic islands (Hawaii, Kerguelen, etcetera,) may owe their origin to juvenile carbon dioxide, but in no case is it possible to exclude the possibility that marine limestones underlie the respective volcanoes and furnished resurgent carbon dioxide to the magmas.

These speculations have little other value than that they show the inadvisability of trying to explain all alkaline rocks in the same way. However, most of the theoretical suggestions of this paper may be generalized as a plea for the recognition of magmatic gases, largely of resurgent origin, as powerful agents in the segregation of alkaline magmas from the subalkaline. The process represents a special case in the differentiating effects of the "fluides minéralisateurs." The writer is inclined to go further than Michel Lévy and other advocates of this theory and definitely to coordinate most of the alkaline rocks with syntectic magmas composed of subalkaline magmas and calcareous sediments.

General Conclusions

The results of this study belong to two different orders. In part they are clearly facts, restated or newly stated and independent of theory; in part the results are hypothetical, and the value of these depends on their finding position in a stable petrogenic theory.

Among the facts needing emphasis in a general treatment of the alkaline rocks are the following:

1. The alkaline rocks are seldom, if ever, found without associated subalkaline rocks. Of the latter those derived from basaltic or gabbroid magma are the types most constantly associated.

2. Either as individual masses or in total volume the visible alkaline bodies are incomparably less important than the subalkaline bodies. The ratio of the total volumes is in the order of magnitude of one to one hundred. This ratio applies very nearly to the Atlantic basin as well as to the Pacific basin. As the Pacific basin is being explored, more and more alkaline masses are discovered. The division of igneous rocks into Atlantic and Pacific branches, as advocated by Becke, Harker, Prior, and others, is not warranted by the facts of distribution, and is not so safely made as the division into alkaline and subalkaline branches.

3. Many of the so-called subalkaline rocks are richer in soda and potash than many of the so-called alkaline rocks. There is no a priori reason why, under certain conditions, subalkaline magmas should not yield typical alkaline rocks by differentiation. For example, a small body of phonolite could be differentiated from a large body of basaltic magma without giving a femic pole strange to petrography.

4. Many alkaline igneous types are chemically and mineralogically transitional into subalkaline types.

5. At least two-thirds of the alkaline rock districts of the world contain thick masses of limestones, dolomites, or other calcareous sediments which have been cut by the alkaline eruptives. For the remaining cases, except, possibly, the Cripple Creek district, information is lacking as to the precise nature of the intruded formations.

6. Many of the minerals special to the alkaline rocks are among those known to form in silicate melts or magmas which have dissolved limestone or other carbonate. The list of such minerals includes primary cancrinite, primary calcite, haüynite, melilite, scapolite, wollastonite, garnets, titanite, graphite, analcite, perovskite, etcetera.

7. The most typical alkaline rocks are so low in silica that feldspathoids, instead of feldspars, crystallize out.

The theoretical suggestions derived from these facts may be likewise summarized:

1. The alkaline rocks have been derived from the steadily associated subalkaline magmas. Phonolites, many nephelite syenites, nephelite basalts, nephelinites, leucite basalts, leucitites, melilite basalts, tephrites, basanites, trachydolerites, theralites, etcetera, appear to be genetically connected with common feldspar basalt. In some cases, like the nephelite syenites of eastern Ontario, typical alkaline bodies are syngenetic with granites, which themselves, in probably all instances, cut calcareous sediments.

2. The segregation of the alkalies and the observed desilication of the subalkaline magmas are largely explained by the assimilation of the natural carbonates. It is conceived that the whole of the carbonate may take part in the appropriate chemical reactions; or that sometimes the subalkaline magma is affected only by the carbon dioxide which is driven off from invaded limestone by magmatic heat into the volcanic vent or other magmatic chamber. Various suggestions are offered as to the nature of the reactions, but they are all strictly tentative and need checking by physico-chemical experiments. Evidence is given for the view that, independently of the other reactions, one or both of the principal alkalies are caused to migrate positively, giving such types as tephrites and leucite

basalts from the differentiated syntectic of carbonate with feldspar basalt. It is conceivable that dolomite and pure limestone have different effects in the reactions, the one concentrating more soda, the other more potash.

3. The amount of natural carbonate required to develop an alkaline differentiate is seen to be small, as compared with a given volume of subalkaline magma.

4. The minerals peculiar to, or characteristic of, alkaline rocks find explanation on the hypothesis proposed.

5. Many alkaline granites and feldspar syenites have no apparent genetic connection with limestones, and to some of these igneous types the carbonate-syntectic hypothesis is not extended. They are often, however, differentiates from subalkaline magmas like granodiorite, etcetera. Many of the syenites cut thick series of sediments other than limestone. The solution of these other sediments with subalkaline magma must upset its chemical equilibrium. Whether alkaline differentiates would result is a question the discussion of which is fraught with yet greater physicochemical difficulties than that above outlined. No attempt is made to answer this question, which involves more or less special conditions for each of the different localities. Some of the alkaline feldspar syenites cut both silicious and calcareous sediments. Their origin is made clearer by an experiment by Schweig, who showed that if molten nephelite syenite is saturated with silica, the resulting syntectic is approximately the average pulaskite.[10]

The possibility is recognized that juvenile as well as "resurgent" carbon dioxide (with other gases) may, in some cases, have accumulated in subalkaline magmas, which have differentiated, giving alkaline poles similar to those derived from syntectics with limestone. For the Cripple Creek phonolitic rocks a special mechanism for the accumulation of juvenile gases is suggested, but it is possible that the abundant carbon dioxide of the mine workings there emanates from limestone stoped down by the pre-Cambrian granites. Analogous difficulties are found in applying the general hypothesis to a few other districts, including Red Hill, New Hampshire; the Great Rift Valley of Africa; some of the Brazilian occurrences, etcetera. For these cases the petrologist needs more data from the field geologist, especially as to the nature of the formations making roofs and walls of the eruptive masses. Many papers, lacking in this fundamental statement, are almost useless to the student of petrogeny.

6. Generalizing, the alkaline rocks may be regarded as differentiates of syntectics. In most instances the foreign matter dissolved in the sub-

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[10] M. Schweig: Neues Jahrbuch für Mineralogie, etc. Beilage Band 17, 1903, p. 517.

alkaline magma is solid rock, usually carbonate. In others, the foreign matter may be gas, usually carbon dioxide, which has a juvenile origin. This paper has specially discussed the first group of cases. Many of the leading petrologists refuse to credit the syntectic idea with having any general value in the petrogenic problem, but their scepticism is scarcely justified by the facts of the field. In any case it is idle to refuse assent to the proposition that magma with the known volcanic temperatures is capable of assimilating limestones and dolomites.

His own field experience has led the writer to a position much like that held by Loewinson-Lessing, who states that "bisweilen genügt ein Einschmelzen einer unbedeutenden Menge irgend eines fremden Stoffes, der im Magma oder in einem Theil desselben wenig löslich ist, um einen Anstoss zur Spaltung in mehr oder weniger grossem Maasstabe zu geben."[11] The present writer would extend the idea so that large-scale differentiation is regarded as often induced by assimilation of foreign rock-matter which, as such, is entirely miscible with the original magma. The true, compound solutions so produced differentiate according to reactions other than those affecting the pure, original magma. Thus, for example, augite andesite is a differentiate of basalt; nephelinite is one of the differentiates from a basalt-limestone syntectic.

The hypothesis is also in line with the older views, since it offers a special instance of the action of the "fluides minéralisateurs," which have been so long emphasized by the French workers in petrogenic theory.

A complete genetic study should discuss the many alkaline types individually. This is not attempted, for the detail of their differentiation is not essential to the main thesis of this paper. An inspection of the literature of the tabulated occurrences shows that magmatic splitting has often taken place in successive stages. That gravity may be in control throughout is suggested by the conditions at Square Butte and Shonkin Sag, Montana. In each of these localities alkaline syenite overlies shonkinite, and both types have been derived from a magma with the composition of leucite basalt. The method of the differentiation is like that in the more acid syntectics of the Moyie, Pigeon Point, and Sudbury sheets; and the general importance of gravitation (with separation of salic and femic constituents) in magmatic splitting is attested by a multitude of other facts of the field.[12] In other words, the alkaline magmas seem to obey the same general laws as those affecting the more voluminous subalkaline

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[11] F. Loewinson-Lessing: Compte Rendu de la VII[me] session, Congrès géologique international, Saint Petersburg, 1897 (1899), p. 380. See also p. 358.

[12] See American Journal of Science, vol. 20, 1905, p. 185, and Festschrift zum siebzigsten Geburtstage von Harry Rosenbusch, Stuttgart, 1906, p. 203.

magmas. The chemical contrasts between the two groups are explained by the assimilation or syntectic theory, as that theory also recognizes the principal importance of magmatic differentiation.

The writer is not able to make Jensen's hypothesis as to the origin of alkaline rocks agree with the known facts of rock distribution and with chemical relationships.[13] The general association of alkaline rocks with sediments is here explained in a quite different way. Jensen's conclusion that most of the alkaline rock eruptions are of late geological dates may possibly bear on the limestone-syntectic hypothesis, since it has taken much of geological time to accumulate the thick masses of calcareous sediments which are cut by alkaline bodies.

Finally, the general thesis explains the localization of rock types occurring in the alkaline "petrographic provinces." The Norwegian, Bohemian, Italian, Monteregian, Montanian, Texan, Australian, Tasmanian, and other provinces are alkaline with respect to igneous types and calcareous with respect to their sediments; and no one of these provinces lacks subalkaline eruptives. Yet explanation is not proof; this must await the discovery of many new facts and the judgment of physical chemists cooperating with field geologists. The alkaline group of igneous rocks seems to offer a specially valuable test of any petrogenic theory.

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[13] H. J. Jensen: Proceedings of the Linnean Society of New South Wales, vol. 33, 1908, p. 491.

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EVIDENCE THAT THE FOSSILIFEROUS GRAVEL AND SAND BEDS OF IOWA AND NEBRASKA ARE AFTONIAN[1]

BY B. SHIMEK

(*Presented by title before the Society December 30, 1909*)

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[1] Manuscript received by the Secretary of the Society December 30, 1909.

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Previous Discussions

About a year ago the writer announced[2] the discovery in western Iowa of Aftonian sands and gravels containing mammalian and molluscan remains.

Subsequently Calvin included a brief discussion of the same deposits in his presidential address,[3] and in the same volume[4] described the mammalian fossils in detail.

In none of these papers was an effort made to present the full evidence on the basis of which the reference to the Aftonian was made, and the correctness of this reference has been questioned recently in private correspondence.

At the December, 1908, meeting of the Geological Society of America the writer presented a paper,[5] the publication of which was somewhat delayed,[6] in which this question was discussed to some extent, but no special emphasis was placed upon the fossiliferous portions of the formation.

Importance of the Aftonian mammalian Fauna

CORRELATION WITH OTHER DEPOSITS

The discovery of a distinct Aftonian fauna is not only of interest and value in itself, but it has an important bearing on a number of interesting questions.

Thus it may make possible the closer correlation of formations like the *Equus* beds, Sheridan beds, etcetera, which contain practically the same mammalian fauna.

EVIDENCE OF CLIMATIC CONDITIONS

Moreover, the presence of this fauna makes possible for the first time

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[2] Science, vol. xxviii, 1908, p. 923.
[3] Bull. Geological Society of America, vol. 20, 1909, pp. 137-139.
[4] Ibid., pp. 341-356.
[5] Read by title.
[6] Bull. Geological Society of America, vol. 20, 1909.

the more accurate determination of the climatic conditions which prevailed during the Aftonian interglacial period.

Some light is thrown upon these conditions by the presence of a mammalian fauna made up of large herbivorous animals, which probably required great quantities of plant food and could live only in a climate supporting abundant terrestrial plant life. While all these species of mammals are now extinct and it is not entirely safe to draw conclusions concerning habits from mere relationship, it seems reasonable to conclude that the climate was sufficiently mild to support the necessary plants.

Significance of the Aftonian molluscan Fauna

THE AFTONIAN MOLLUSKS

The molluscan fauna, though apparently insignificant when compared with the giant mammals which were discussed by Calvin, furnishes evidence concerning climatic conditions which is really much more conclusive, for the mollusks of the Aftonian are identical with those which inhabit Iowa and adjacent territory today, and the habits of all these species are definitely known.

But the very fact that these species exist today introduces an element of possible error which makes the exact determination of the horizon from which they come very necessary; for similar or identical series of shells may be collected both in our present waters and in very modern alluvial deposits, and these species probably invaded the region of Iowa during every interglacial period of Pleistocene time.

The following species of mollusks have been collected by the writer from the Aftonian beds in Iowa:

Aquatic Species

Unio metanever Raf.	*Ancylus rivularis* Say.
Unio anodontoides Lea (?).	*Lymnæa reflexa* Say.
**Sphærium sulcatum* (Lam.) Pr.	**Lymnæa caperata* Say.
**Pisidium* ——, probably 2 species.	**Lymnæa humilis* Say.
**Amnicola* ——.	**Physa* ——.
**Bythinella obtusa* (Lea) St.	**Planorbis bicarinatus* Say.
**Valvata tricarinata* Say.	**Planorbis parvus* Say.
Valvata bicarinata Lea.	**Planorbis dilatatus* Gld.

Terrestrial Species

Polygyra —— (fragment).	*Zonitoides arboreus* (Say) Pils.
Pyramidula alternata (Say) Pils.	*Bifidaria armifera* (Say) Sterki.
Pyramidula striatella (Anth.) Pils.	*Succinea ovalis* Say (=*obliqua* Say).
**Vallonia gracilicosta* Reinh.	**Succinea avara* Say.
**Vitrea hammonis* (Ström.) Pils.	*Succinea retusa* Lea.

In number of individuals the aquatic species predominate, the land shells being represented by but few specimens, which were evidently washed from near-by land surfaces.

These land species are all living in Iowa today, and their presence in the Aftonian is especially suggestive, since land shells suffer much more from climatic changes than do the aquatic species. Their presence proves the proximity of plant-covered land areas similar to those which now prevail in the region under discussion, and a climate not materially different from that which is found in Iowa today, at least so far as temperature is concerned.

COMPARISON WITH MODERN MOLLUSKS

In order that this similarity of Aftonian and modern molluscan faunas may be more fully appreciated, a comparison is here made between the fossils of the foregoing list and a series of shells dredged in Miller Bay, West Lake Okoboji, Iowa,[7] during August, 1908.

This bay forms a regular rounded indentation in the west shore of the lake. The dredging was done in shallow water, 4 to 8 feet in depth, near the head of the bay, just opposite the Iowa Lakeside Laboratory.

All the species in the foregoing list which are marked with an asterisk were also dredged from Miller Bay. Where only generic names are given, the Aftonian specimens are more or less imperfect, but apparently identical with species collected in the bay.

Unio anodontoides Lea (=*Lampsilis anodontoides* (Lea) Baker) and *Unio metanevrus* Raf. (=*Quadrula metanevra* (Raf.) Simp.) of the Aftonian seem to find substitutes in *Unio luteola* Lam. (=*Lampsilis luteolus* (Lam.) Baker) and *Anodonta* —— of the bay; *Valvata bicarinata* is found living in other parts of Iowa today; *Ancylus rivularis* is now common in the Des Moines River, less than 20 miles away, and *Lymnæa reflexa* is common in ponds in the vicinity of the lake and on other parts of the lake shore.

The bay also yielded 4 additional species of *Planorbis*, 2 of *Lymnæa* and 1 of *Bulinus*, all these aquatic and evidently living in the bay or in ponds communicating with it. The similarity of the aquatic fauna of the bay to the aquatic fauna of the Aftonian is striking. It is a fauna belonging to the larger streams and lakes, and is unlike the terrestrial fauna with its occasional small-pond pulmonates which characterizes the loess.

It will also be noticed that three of the terrestrial species occurring in the Aftonian were also dredged from the bay. Two specimens of *Succinea*

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[7] Lake Okoboji is in northwestern Iowa, and the terrestrial molluscan fauna of its vicinity is practically the same as that of the region of the Aftonian exposures herein discussed.

avara and one each of *Vitrea* and *Vallonia gracilicosta* were secured in this way, together with one specimen of *Vallonia parvula* Sterki, a species not known from the Aftonian.

It is important to note the small number of terrestrial shells which find their way to the bottom of the bay, especially since terrestrial species are abundant in the groves bordering the bay, and great numbers of them are carried out on the lake by freshets to be thrown ashore again. This was well illustrated during the past summer, when great numbers of shells, largely terrestrial species, were thrown out on the north shore of Miller Bay. This bay is bordered by native forest on the west and south shores, and in these groves dwell more than 25 species of terrestrial mollusks, some of them in large numbers. The dead shells of these species, often perfectly fresh, are washed into the bay, and are driven to the north shore by the prevailing southerly or southwesterly winds, where they are literally massed in thousands on the flat beach,[8] together with aquatic species from the bay itself. Yet notwithstanding the great number and variety of forms[9] which are so carried across the bay, but few find their way to the bottom, as was shown by dredging.

EVIDENCE OF CLIMATIC AND SURFACE CONDITIONS

If now we apply approximately the same ratio to the terrestrial mollusks which are found in the Aftonian, we will find the terrestrial species even more abundant, and the climatic and surface conditions which made their existence possible much more general and widespread than might appear possible from the study of the extent of the Aftonian deposits themselves; for, with the exception of these few land shells, the evidence furnished by the Aftonian points to great floods, as the deposit was evidently largely formed by strong currents; yet the presence of these land shells (together with the presence of large terrestrial mammals) is sufficient to show that extensive land areas did exist.

Importance of exact Determination of Aftonian Horizon

In view of the foregoing considerations, it is important that, so far as possible, all doubt concerning the stratigraphic position of the beds which

[8] No forest suitable as a habitat for these species occurs on the slopes adjacent to the north shore of the bay, and the only possible source of these shells is on the opposite, or southerly, side of the bay.

[9] In the drift material on the north shore of the bay the writer found the following aquatic forms: 1 species of *Pisidium*, 1 *Amnicola*, 1 *Valvata*, 5 *Planorbis*, 1 *Segmentina*, 4 *Lymnæa*, and 1 *Bulinus*. Mingled with them in greater numbers were the following terrestrial forms: 1 species of *Carychium*, 1 *Euconulus*, 2 *Zonitoides*, 1 *Vitrea*, 1 *Pyramidula*, 1 *Helicodiscus*, 1 *Punctum*, 1 *Strobilops*, 5 *Bifidaria*, 3 *Vertigo*, 1 *Pupoides*, and 1 *Cochlicopa*. Hundreds of specimens of several of these species were collected.

yield fossils of such interest be set at rest. For that reason the writer presents here a detailed account of the evidence of stratigraphic position furnished by each of the twenty fossiliferous exposures which have been studied in Iowa and Nebraska, and also includes a list of the fossils obtained from each, in order that the distribution of these fossils may be more clearly set forth.[10]

Evidence that Beds are Aftonian

GENERAL CHARACTERISTICS OF THE AFTONIAN

While specific attention is here given to the exposures of fossiliferous Aftonian, it should be borne in mind that there are many more exposures in the same region which have yielded no fossils, but which possess Aftonian characteristics to a greater or lesser extent. Not every exposure presents equally conclusive evidence, and some of the exposures would probably be unintelligible but for the light which comes from the study of the entire series.

Whatsoever may be the variation in this respect, it seems to be restricted within definite limits, for there are certain characteristics which prevail to such an extent that they may be regarded as collectively determining typical Aftonian, and while not all of them are present in every section, yet in the great majority of cases they are sufficiently well developed to make the identification entirely satisfactory.

COMPOSITION AND STRUCTURE

The composition and structure of the Aftonian beds, while somewhat variable, are sufficiently constant to assist materially in the identification of this formation. In the western part of Iowa and in eastern Nebraska they consist of gravel, sand, and fine silt, variously cross-bedded and interstratified. Usually each of these types of material appears distinct in a well defined wedge or stratum, and this segregation evidently represents local variation in the force of the currents. Sometimes only one or two of them make up the deposit, but more frequently all three types will be found in the same exposure, though varying very much in relative amount. Sometimes they are in part blended or mixed. Occasionally, especially where disturbed by the overlying Kansan, the Aftonian contains masses of Nebraskan or Kansan till. Very large boulders, usually granite or Sioux quartzite, sometimes occur in the sandy or gravelly parts.

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[10] The mammalia mentioned throughout this paper were identified by Professor Calvin, the mollusks by the writer. The collections and the stratigraphic studies in the field were made chiefly by the writer for the Iowa Geological Survey.

The gravels vary in coarseness and composition, but the pebbles are commonly water-worn and frequently stained with iron to a deep rusty red. The sands are sometimes similarly stained, but vary to a pure white.

Both sands and gravels almost universally show black streaks, bands, and cloudings of MnO_2.[11]

Very soft, small, white nodules of $CaCO_3$ are also usually present in the sandy and gravelly parts.

The silt is usually yellowish, bluish, or nearly white and appears in thick strata, or more frequently in smaller plates and layers. It commonly shows lamination, and sometimes it is more or less mingled with sand.

In some parts of Iowa peat beds also occur, but they are practically absent from the western beds.

DISTRIBUTION OF FOSSILS

Much of this western Aftonian is fossiliferous. Twenty fossiliferous exposures have been carefully studied. Of these 1 is in eastern Nebraska, 18 in western Iowa, and 1 in eastern Iowa. Non-fossiliferous exposures were studied in much greater numbers in both states.

Of the twenty fossiliferous exposures, eight yielded mammals only, seven yielded mollusks only, and five contained both mammals and mollusks.

STRATIGRAPHIC RELATION, PLEISTOCENE SECTION

These fossiliferous beds lie unconformably between the Nebraskan (pre-Kansan) drift below and the Kansan above, and are interglacial and Aftonian.

This was first clearly shown to the writer in the county line exposure in the northern part of Harrison County, Iowa, where both tills are present, though he had in the Cox pit previously determined that they are below the Kansan.

Both tills are not always present, but the Pleistocene members which are present always maintain a consistent relative position, excepting in those limited local cases where the Kansan caused a little confusion by plowing up the Aftonian and Nebraskan.

In this connection a section of the Pleistocene of western Iowa may be of interest. The Pleistocene rests on the older rocks, which vary with locality, but in western Iowa are usually Missourian or Cretaceous.

Passing upward, a complete section will reveal the following:

[11] The presence of so much MnO_2 also indicates the occurrence at one time of large quantities of organic matter.

7. A yellow loess, light both in color and texture, probably post-Wisconsin, found only near the Missouri Valley, and blending more or less with (6).

6. A yellow, rather heavy loess, probably post-Iowan, blending with (7) and sharply separated from (5).

5. A bluish gray, compact post-Kansan loess, very variable in thickness.

4. The Loveland—a heavy joint clay, usually reddish, evidently belonging to the melting period of the Kansan, reaching at least 40 feet in thickness.

3. The Kansan drift, very variable in thickness.

2. The Aftonian gravel, sand, and silt, up to 40 feet in thickness.

1. The Nebraskan drift (pre-Kansan), which varies up to at least 40 feet in thickness, but the greater part of this buried under other deposits.

The total thickness of 5, 6, and 7 does not exceed 35 feet on the west side of the Missouri and rarely reaches 90 feet on the Iowa side.

DETAILED DESCRIPTION OF FOSSILIFEROUS SECTIONS

Order of treatment.—For convenience the sections are taken up in geographical order and are numbered consecutively, the general order being from north to south.

1. *Akron section.*—This was made in sinking a well on the Severin Jensen farm, in the northwest quarter of section 33, township 93 north, range xlviii west, about 2 miles east of Akron, Iowa.

The well is located on a gentle slope of one of the swells or ridges by which the typical rolling Kansan of this region gradually drops down to the valley of Beaver Creek a half mile north. The Kansan is here covered with loess, which is more or less fossiliferous, as at the quarter-section corner on the north line of section 32 and in the cellar of the Searles house mentioned below.

Mr. Jensen reports his well as 24 feet deep and reaching down to a "hard-pan" (probably Nebraskan drift). A somewhat deeper boring brought up "little pieces of slate" (probably Cretaceous shale).

Resting on this hard-pan are 7 or 8 feet of sand and gravel. At a depth of about 20 feet a bed of very ferruginous sand was encountered, and in this were found the bones and teeth of *Mammut mirificum.*

Above the sand and gravel (Aftonian) there is a bed of hard clay mixed with a little sand and gravel. A part of this was dark in color. This is evidently Kansan drift with Loveland joint clay.

The topmost layer is a softer yellow clay, evidently loess.

The owner had made several attempts to sink wells within a few rods of the present well. In one of these he found stratified water-bearing sand at a depth of 12 feet. In another near by he reached a "black hard-pan" (evidently Nebraskan), with a little sand and gravel (seemingly Aftonian) resting on it.

The following fossils were obtained from the Jensen well:

212.[12] *Mammut mirificum*, 2 molars (see Bulletin of the Geological Society of America, volume 20, plate 27).
216. Cranial bones of the same species.
217. Fragments of tusk of same species.
221. Homologue of the first and second phalanges of sloth.
Unidentified fragments of bone.

2. *Searles section.*—This is also a well section, reinforced by an excavation for a cellar near by. It is located a quarter of a mile west of section (1) and at a point somewhat lower.

The section as reported by Mr. Searles is as follows:

Dark brown surface soil, 3 to 4 feet.
Yellow clay, 12 to 13 feet.
Blue joint clay with boulders, 1 to 2 feet.
Sand, 2 feet.
Gravel, about 6 feet.
Shale, about 30 feet penetrated.

The yellow clay is probably loess and Loveland joint clay, these two usually being confused by well-diggers; the blue joint clay is evidently Kansan drift; the sand and gravel belong to the Aftonian, and the shale is Cretaceous.

The cellar, which is east of the well and a little lower, showed 4 to 5 feet of loess resting unconformably directly on a layer of gravel 1 to 2 feet in thickness, and this rested on fine sand. The sand and gravel are evidently Aftonian, the former containing fragments of shells of *Sphærium*, probably *S. sulcatum*.

The conclusions concerning the identity of the several strata in sections (1) and (2) are further strengthened by the fact that other sections in this region show a corresponding arrangement. The best of these sections, so far as the writer observed, is that in the first cut along the Chicago, Milwaukee and Saint Paul Railway 2 miles north of Chatsworth and about 8 miles north of the Jensen well.

Here about 18 feet of loess rest on a mass of Loveland and typical Kansan drift which is separated from the underlying dark Cretaceous shale by a distinct stratum of Aftonian sand and gravel. The Kansan and Aftonian are unconformable and are separated by a strongly oxidized ferruginous band.

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[12] The numbers preceding the names of mammals in the lists included in this paper are Museum numbers, the specimens being deposited in the Geological Museum of the State University of Iowa.

3. *Anderson section.*—This is in a sand pit located in the southeast quarter of the northwest quarter of section 13, township 89 north, range xlviii west, north of North Riverside, Sioux City, Iowa.

The section shows the following members:

Loess, 8 to 12 feet.
The Loveland, an irregular mass of reddish joint clay.
Kansan typical bluish till, 6 to 8 feet.
Fine laminated bluish or yellowish silt, evidently Aftonian, 5 to 8 feet.
Aftonian sand, cross-bedded with streaks of MnO_2 and iron, and containing mammalian fossils, 22 to 30 feet.

Mr. Anderson reports larger boulders and gravel under the sand resting on rock.

The following fossils were collected in the Aftonian sand and gravel:

174. *Megalonyx* ——, ungual phalanx.
175. *Megalonyx* (?) ——, patella.
176. A canine tooth, not identified.
178–181. *Equus complicatus*, various teeth.
Various fragments of bones and teeth, not identified.

4. *New Woodward section.*—This is a new sand pit located in the southwest quarter of section 9, township 85 north, range xliv west, about 2 miles southwest of Rodney, Iowa. This exposure shows about 3 feet of fine, white, cross-bedded sand containing shells of mollusks, and above it an irregular mass of sand and gravel about 8 feet deep.

The material lying above the sand is not clearly defined, on account of slumping, but it is mixed drift and gravel, such as is common in this region, where the Kansan plowed into the upper part of the Aftonian.

The sand contains silt balls or pellets, such as are common in the Aftonian, and in all respects the structure and composition of the beds are typical. Moreover, several sections in the vicinity show the unmistakable presence of the Aftonian—one, located in Woodwards Glen, in the southwest quarter of section 17, showing a distinct layer of Nebraskan drift[13] immediately below the Aftonian.

The following mollusks were collected in the white sand in section (4):

Pisidium ——.
Sphærium ——, probably *S. sulcatum*, fragments.
Lymnæa ——, probably *L. humilis*, broken.

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[13] The pre-Kansan, or sub-Aftonian drift, was named *Nebraskan* in Science, n. s., vol. xxxi, pp. 75-76, January 14, 1910. The name also appears in the Bulletin of the Geological Society of America, vol. 20, p. 408, dated December, 1909, but not distributed until after the publication in Science.

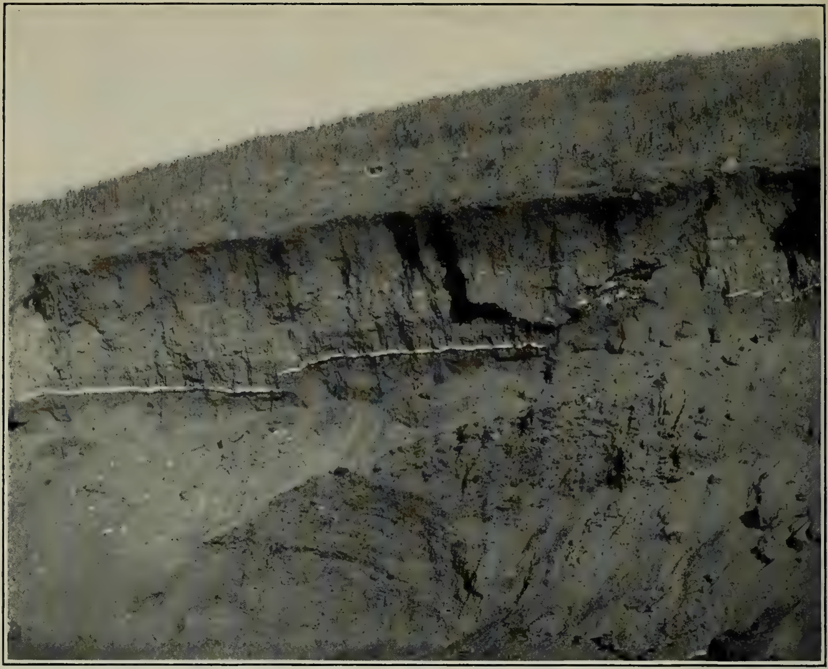

FIGURE 1.—WENIGER PIT

The irregular white line is the calcareous nodular band separating the Kansan drift from the Aftonian below

FIGURE 2.—PART OF THE ELLIOTT SECTION

Darker Kansan separated from cross-bedded Aftonian by sharp, somewhat oxidized line

SECTIONS SHOWING CONTACT OF KANSAN AND AFTONIAN

5. *Weniger pit.*—This is a sand pit located in the east half of section 18, township 84 north, range xliv west, in Monona County, Iowa, in the bluffs facing the Missouri Valley. It shows 8 feet of sand and gravel on which typical Kansan drift, 2 to 4 feet thick, rests unconformably. The two deposits are separated by a distinct oxidized band and by a layer of calcareous nodular plates (see plate 2, figure 1).

The Aftonian here rises to about 40 feet above the Missouri bottoms, the average altitude of these beds in this territory.

Fragments of shells, probably *Sphærium,* were found in the upper, finer sand.

6. *Elliott pit.*—This is a sand pit located in the northeastern part of Turin, Iowa. The sand and gravel in this pit are typically Aftonian in the cross-bedding, streaking with iron and MnO_2, the presence of silt and drift nodules or pellets and white, soft, calcareous nodules, the occurrence of mollusks in the sand and mammalian remains in the gravel.

Moreover, the position of these beds removes all doubt as to their identity. Superintendent W. E. Babcock, of the cement tile factory operating this pit, reports that in boring in the pit they encountered, below the sand and gravel, a layer of "dark clay which was like rubber," into which they penetrated about 4 feet. They found it putty-like, tough, very hard to work, and containing occasional boulders. This is evidently Nebraskan drift, which is also well exposed in the same valley at Castana.

The Aftonian was exposed to a depth of about 12 feet. In the greater part of the exposure the fine sand lies above the gravel, though there is some interbedding, but near the south end a layer of coarse, ferruginous gravel rests on the sand.

The bones and teeth were found in gravel at a depth of 10 to 12 feet below the top of the Aftonian.

A distinct band of bluish or reddish laminated silt was found above the sand and gravel. It is about 2 feet thick, and evidently represents a slack-water deposit of the Aftonian. It grades downward into fine sand.

The superimposed formations, the Kansan drift, the Loveland, and the loess, are well developed, and the entire section is typical. The sharp contact line between the Kansan and Aftonian is shown in plate 2, figure 2.

The following vertebrate fossils were collected:

8. *Elephas* or *Mammut*, a cervical vertebra (see ibid., plate 25, figure 8).
161. Part of rib of proboscidian.
166. *Mammut americanum*, sixth molar.
187. *Camelus* ——, first phalanx.

122, 136. *Equus scotti*, superior molars.
227. *Equus scotti*, lower molar.
184. *Equus complicatus*, premolar.
229. Incisor of horse (?).
Miscellaneous bones and teeth of Equus: 4 cannon bones (169); phalanges (171-172, 195); a tooth (199), and fragments of teeth (228).
232. *Equus* ——, left radius (proximal end).
197. Jaw of ruminant, fragment.
230. Premolar of animal related to camel.
231. Foot bones of camel (2).
Various unidentified bones, mostly fragmentary.
Vertebra of a fish. Found in fine sand.

Mollusks

Unio anodontoides Lea (?).
Unio ——, fragments of a heavier species.
Sphærium sulcatum.
Pisidium ——.[14]
Amnicola ——.
Valvata tricarinata.
Valvata bicarinata.
Ancylus rivularis.
Lymnæa caperata.
Planorbis parvus.
Segmentina armigera.
Pyramidula alternata.
Pyramidula striatella.
Vallonia gracilicosta.
Vitrea hammonis.
Zonitoides arboreus.
Bifidaria armifera.
Succinea ovalis.
Fragments of 2 or 3 other species.

7. *Ordway pit.*—This is located in the bluff on the southwest side of the Maple River, opposite Castana, Iowa, in the southeast quarter of section 13, township 84 north, range xliv west.

The Aftonian here rises about 40 feet above the Maple bottoms. The section shows the following members present:

Loess, abundant on the ridge above the section.
Loveland, 5 to 6 feet.
Kansan drift, 6 to 18 feet.
Aftonian: fine, cross-bedded, with interstratified silt and other characteristics of typical Aftonian, 5 to 8 feet.
Aftonian ferruginous gravel, in part forming conglomerate plates, 3 to 4 feet.

Both this and the following section are on a Kansan sloping bench with no overlying loess. The loess begins higher up on the slope, and the ridge is capped with a thick deposit of it.

In the northern part of the same pit a layer of gravel 3 feet in thickness lies under the sand, and contained a stratum of mussel shells (mostly

[14] The species of *Pisidium* has not been determined, the recent revision of the genus making this more difficult, but it seems to be identical with the most common species now living in the northwestern part of the state.

heavy-shelled *Unio*) in which the shells were closely massed. They were very fragile and could not be taken out entire. With them were shells of *Sphærium sulcatum* and a shell of *Ancylus rivularis*. Several large boulders rested on this gravel layer.

The finer sand contained the following mollusks:

Unio ——, fragments.
Sphærium sulcatum.
Pisidium ——.
Valvata tricarinata.
Planorbis bicarinatus.
Planorbis dilatatus.
Segmentina armigera.
Physa ——, fragment.
Ancylus rivularis.
Succinea retusa.
Succinea avara.

8. *Ordway well.*—This well was excavated on the same terrace-like slope, about an eighth of a mile northeast from the pit.

Measurements of the well section could not be made, but it was plain that the Kansan reaches the surface here, and may be traced upward for 30 feet more (vertically) before it disappears under the loess which covers the ridge in its upper parts. In the well itself bluish Kansan till was clearly discernible. Below this Aftonian sand, with a little gravel, rested on a deep bed of Nebraskan drift. The man who dug the well claimed to have bored into the blue-black "hard-pan" (Nebraskan drift) to a total depth of 175 feet.

An examination of the materials brought up from the well corroborated the correctness of the record. The sand is here clearly interglacial, lying between the Kansan and the Nebraskan drift sheets, and hence Aftonian.

The sand in the well section yielded the following fossils:

Unio ——, fragments.
Sphærium sulcatum.
Pisidium ——.
Valvata tricarinata.
Planorbis bicarinatus.

Some years ago a fragment of a large scapula was obtained from an old gravel pit near this well, and it has been added to the collection (number 91).

9. *Griffin well.*—This is located near Mapleton, Iowa, on the farm of C. H. Griffin, on the east side of section 17, township 85 north, range xlii west. It is situated in a rolling Kansan area about 50 feet above the valley of Heisler Creek.

The section was made through loess, Kansan drift, and into Aftonian sand and gravel to a depth of about 40 feet. The writer examined the material taken from the well. Moreover, Kansan appears at the surface on the same slope at a lower level, the loess covering only the upper parts of the ridge. At a depth of 35 feet a part of the tooth of *Elephas imperator* was found in the gravel.

10. *Wilkenson well.*—This is located in the northwest quarter of section 6, township 85 north, range xlii west. Here, in a typical Kansan drift region, a large tusk (234), a molar, and fragments of cranial bones (numbers 204-211) of *Mammut americanum* were found at a depth of about 35 to 40 feet, in loose sand and gravel. This section is similar to number (9).

11. *Hawthorn pit.*—This is a sand and gravel pit in the same region, being located in the northwest quarter of section 14, township 85 north, range xliii west.

The section is typical, showing loess, Loveland, Kansan drift, and Aftonian, the latter here chiefly sand. Mr. C. A. Hawthorn discovered bones in this at various times, but none were saved.

12. *McCleary pit.*—This is also located in the same region, in the southwest quarter of section 1, township 84 north, range xlii west. The pit is remarkable because it is situated more than two miles inland from the line of the Maple River bluffs, on a small tributary creek. It shows distinct plowing by the Kansan, which here lies distinctly above a stratum of typical Aftonian sand, with some gravel, about 12 feet in depth. The owner reported that in the gravelly portions of the pit he has found "regular clam shells."

13. *County line exposure.*—This is a section made by a road cut along the Little Sioux River, in the north half of section 5, township 81 north, range xliv west, less than half a mile south of the Monona and Harrison County line. The road is here about 25 feet above the Little Sioux River and parallel with it. Three cuts appear in close proximity, making an almost continuous section more than 500 feet in length. The southernmost of these cuts is the best and shows the following:

5. Loess, appearing above the cut and ascending to top of bluff.
4. Loveland, a reddish joint clay, with lines of very large calcareous nodules, more than 15 feet.
3. Kansan, typical bluish, very calcareous till, 12 feet.
2. Aftonian:
    - Fine whitish silt, about 15 feet.
    - Fine silt, mixed with sand, shell-bearing, 5 feet.
    - Coarse gravel, very ferruginous, about 7 feet. This reaches 10 feet in the northernmost cut.
    - Fine cross-bedded sand, 6 to 12 feet.
1. Nebraskan drift, 10 feet exposed, but running out both ways.

More detailed notes on the members of this section follow:

(1.) The Nebraskan is typical blue-black till, breaking up into very small blocks, and containing scattered pebbles and boulders. It is exposed along the road for a distance of about 65 feet, and its upper line is very irregular, but sharply defined. The Aftonian, which lies unconformably on it, has a very ferruginous band at its base.[15]

(2.) The Aftonian is more or less variable in the distribution of its materials. In some parts fine silt appears above, and the sand and gravel are variously disposed. However, they show the characteristic structure already noted and are typical. Large slabs or blocks of sand-conglomerate are found in the sand beds. The measurements of the several parts of this formation as given in the section are maxima. At no point do these appear together, the total being about 20 feet.

(3.) The exposed parts of the Kansan vary in thickness in the several cuts from 0 to 15 feet. None appears in the northern cut, the Loveland resting directly on the Aftonian.

The Kansan is separated from the Aftonian by a sharp ferruginous line.[16]

(4.) The Loveland consists of typical reddish joint clay and varies from 8 to more than 15 feet in thickness.

The fossils were found in the layer of sandy silt, with the exception of the fragments of *Unio*, which were collected in sand in the northern cut. The list follows:

Unio ——, fragments.	*Planorbis bicarinatus.*
Sphærium sulcatum.	*Planorbis dilatatus.*
Pisidium ——.	*Lymnæa* ——, probably *L. caperata*, fragments.

14. *Peyton pit.*[17]—This sand pit is located in the northeast quarter of section 23, township 81 north, range xliv west. The Aftonian here rises about 40 feet above the Soldier River bottoms and is at least 30 feet thick. It is made up largely of sand, but with beds and wedges of gravel, and it presents all the characters of typical Aftonian.

Near the base of the section a bed of white sand 6 to 8 feet thick appears, and just above it, in sand and gravel, a Sioux quartzite boulder measuring 4 by 2 by 1½ feet was found.

Mr. Peyton reports a dark-blue clay under the sand and gravel. This is probably Nebraskan drift.

The Kansan lies unconformably on the Aftonian, which it has evidently plowed in its upper portions, and is very distinct.

The following fossils were collected, the mammals in gravel and the mollusks in sand:

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[15] See Bull. Geological Society of America, volume 20, plate 34, figure 1.
[16] See ibid., plate 34, figure 2.
[17] See ibid., plate 16, figure 2.

Mammals:

2. *Mammut americanum*, jaw with 4 teeth (see ibid., plate 25, figure 2).
4. *Elephas* —— (?), part of humerus (see ibid., plate 25, figure 4).
6. *Elephas imperator* (?), femur, 4 feet, broken (see ibid., plate 25, figure 6).
7. *Elephas imperator*, sixth molar (see ibid., plate 24).
9. *Elephas* —— (?), scapula, fragment.
157. Limb bone of proboscidian.
18 (*a*). Rib, unidentified.
56. Camel, first phalanx (see ibid., plate 21, figure 1, and plate 22, figure 2).
66. *Equus* ——, acetabulum.
84. *Equus* ——, part of metapodial.

Mollusks:

Sphærium sulcatum.

15. *Wallace pit.*—This is a sand and gravel pit in the bluffs of the Little Sioux (which are also the east bluffs of the Missouri Valley) near the north line of section 31, township 81 north, range xlv west. Here the Aftonian rises to 35 feet above the valley. The lower part of the section was obscured by a talus, but coarse sand, with some gravel, rises distinctly to a height of 20 feet above the valley. Then follows a stratum of mixed and alternating yellow silt and sand for 15 feet. Above this the Kansan is about 10 feet thick, the Loveland 6 to 8 feet, and on the hill above the section the loess rises to the summit.

The Aftonian is typical. Mr. Wallace opened a pit in the same bluff at a point about 60 yards south, and exposed 16 to 18 feet of gravel. The present pit shows sand chiefly. In this fragments of a *Unio*, or related mussel, were found.

16. *Robinson pit.*—It is located in the southwest quarter of section 16, township 80 north, range xliv west, and is a typical Aftonian section, with Kansan drift and Loveland and loess above. The Aftonian rises to a height of about 40 feet above the valley, and is sharply separated from the Kansan by an oxidized band and by large nodular calcareous plates. It contains very little silt, but is made up chiefly of sand and gravel of the characteristic type.

The following mollusks were collected in the sand:

Unio ——, fragments of thick-shelled species.
Sphærium sulcatum.
Pisidium ——.
Valvata tricarinata.
Bythinella obtusa.
Planorbis parvus.
Lymnæa reflexa.
Segmentina armigera.
Polygyra ——, fragments of a large species.
Vitrea hammonis.
Succinea ovalis.

17. *Cox pit.*[18]—This is located in the southeast bluffs of the Boyer River, in the northeast quarter of section 24, township 78 north, range xliv west, and is one of the finest sections of the entire series. The Aftonian here rises to a height of about 35 feet above the Boyer bottoms.

The section shows the following:

4. Loess, capping the ridge above, but not appearing in the pit.
3. Loveland, exposed just above the pit.
2. Kansan, typical bluish calcareous till, 13 feet.
1. Aftonian:
   Sand, varying in coarseness, beautifully cross-bedded, 21 feet.
   Gravel, light colored, cross-bedded, with small boulders, 6 to 8 feet.
   Gravel, dark colored with much MnO_2, 6 to 8 feet.
   Fine bluish silt, 6 inches.
   White sand, penetrated to a depth of 4 feet.

The Aftonian is typical in structure and composition, and both gravel beds contained mammalian and molluscan fossils. No fossils were observed in the sand.

The line between the Aftonian and Kansan is very sharply defined, more or less ferruginous, and with large nodular calcareous plates. Aftonian sand and gravel "boulders," which are scattered through the lower part of the Kansan, also give evidence of plowing by the latter.

The following mammalian fossils were collected:

1. *Elephas imperator*, lower jaw (see ibid., plate 25, figure 1).
16. *Elephas columbi*, molar.
12. *Mammut americanum*, sixth molar (see ibid., figure to left of figure 6, plate 25).
    Mammut americanum, other molars.
42 (*a*). *Mammut americanum*, piece of tusk (see ibid., figure just below left end of figure 4, plate 25).
5. *Elephas* or *Mammut*, right tibia (see ibid., plate 25, figure 5).
18, 25. *Elephas* or *Mammut*, caudal vertebræ.
30. *Elephas* or *Mammut*, pubic bone, part.
138. *Elephas* or *Mammut*, distal end of radius.
45, 46. *Elephas* or *Mammut*, scapula, fragments (see ibid., plate 25, figure 9).
19. Vertebra, unidentified.
57. Incisor, unidentified.
64. *Bos* ——, horn cores (see ibid., plate 23, figure 1).
83. Astragalus of large ruminant (see ibid., plate 22, figure 1).
    Piece of cannon bone of large ruminant (see ibid., plate 22, figure 3).
183. *Camelus* (?), second right inferior molar.

[18] See ibid., plate 2, plate 16, figure 1, and plate 33, figures 1 and 2.

185. *Camelus* (?), second phalanx.
67. *Equus* ——, os calcaneum, 3 specimens.
69. *Equus* ——, proximal end of radius.
72. *Equus* ——, ulna, part.
75. *Equus* ——, scapula, part.
77. *Equus* ——, 3 incisors.
78. *Equus* ——, dorsal vertebra.
79. *Equus* ——, astragalus.
80. *Equus* ——, 4 cannon bones.
81. *Equus* ——, humerus, 2 specimens.
82. *Equus* ——, entire tibia and fragments.
85. *Equus* ——, distal end of femur.
86. *Equus* ——, first phalanx, 3 bones.
87. *Equus* ——, part of large vertebra.
88. *Equus* ——, distal end of radius, 2 pieces.
137. *Equus* ——, distal end of left tibia.
224. *Equus* ——, metacarpal.
70, 120, 123, 126-127, 129-135. *Equus* ——, molars.
116-119, 125, 185. *Equus scotti*, molars (see ibid., plate 18, figures 1-6).
121, 124, 128. *Equus complicatus*, molars (see ibid., plate 19, figures 1-5, and plate 21, figures 2-4).
162. *Mylodon* ——, claw (see ibid., plate 26).
Numerous fragments of bones and teeth.

There were also obtained the following mollusks:

Unio ——, smooth heavy shell.
Unio metanever, 1 valve.
Unio ——, smooth shell.

18. *Peckenpaugh sections.*—These are located on the east side of the Boyer River near the mill-dam, at Logan, Iowa. There are really three sections, but they lie in close proximity and present the same essential facts.

The largest section was made in quarrying rock just above the dam.[19]

The quarry section shows the following formations:

Loess and soil, 20 feet.
Loveland, reddish, somewhat sandy, 6 feet.
Aftonian:
    Sand, cross-bedded, 7 feet.
    Coarse ferruginous gravel, 2 feet.
Missourian limestone, exposed 4 feet.

The water in the Boyer River above the dam is about 5 feet lower than the bottom of this section.

[19] See photograph of this section, ibid., plate 35, figure 2.

A well located just opposite the dam and about 5 rods from the river revealed the following:

Loess, } 23 feet.
Loveland, }
Aftonian:
Colored sand, 4 feet.
White sand, 5 feet.
Coarse gravel, 2 feet.
Missourian limestone, penetrated 4 feet.

The top of the well rises 39 feet above the dam.

The third section is in a sand pit, excavated at the level of the road, which is about 23 feet lower than the top of the well.

The following section was shown:

Aftonian:
Sand and finer gravel, 9 to 12 feet.
Fine silt, about 1 foot.
Coarse ferruginous gravel, 18 inches.
Missourian limestone.

It will be noticed that the Kansan and Nebraskan drifts are wanting in all these sections, but the arrangement of the formations present is consistent with the typical section.

The lowest gravel bed is the only fossiliferous part of the Aftonian in these sections. It yielded the following:

Elephas columbi, a good molar, collected north of the middle of the quarry section.

Fragment of a large scapula (?), with the preceding.

Equus (?), a fragment, probably from limb bone of a horse, was taken from the well.

Part of a rib and a fragment of an unidentified bone were taken from the gravel in the sand pit.

19. *Denison pit.*—This is a railway sand pit located near the northwest corner of section 14, township 83 north, range xxxix west, near Denison, Iowa. It is excavated in a detached knoll in the valley of the Boyer River.

The evidence that the sands and gravels in this pit are Aftonian is perhaps less satisfactory than in any of the other sections discussed in this paper; yet the preponderance of evidence favors their reference to that period.

The pit presents the following section:

Loess, light, yellow or slightly brown stained, 2½ feet.
Fine sand, laminated as in dune formation, 5 to 6 feet.

Loess, heavier, yellow with bluish mottlings and ferruginous lines and cloudings, such as appear commonly in older loess, fossiliferous, 5 to 6 feet.
Aftonian sand and fine gravel, 35 feet.

No drift appears in the section, but the lower loess has the appearance of some of the yellower post-Kansan or oldest post-Iowan loess. It is evidently older than the Wisconsin, which might have also left gravel trains in the valley of the Boyer, as that stream drains Wisconsin border territory.

The dune sand layer may correspond to similar formations which are common along the border of the Iowan drift and which were evidently formed in immediately post-Iowan time. The structure of these sands and gravels, their position under an old loess, and their fossils seem to warrant their reference to the Aftonian.

The following fossils were obtained from this part of the pit:

21. *Elephas primigenius*, molar (see ibid., plate 23, figure 2).
28, 29. *Elephas* —— (?), tusks, 2 pieces.
Cervalces ——, part of antler.
Sphærium, probably *S. sulcatum*, fragments.

20. *Offerman pit*.—This sand and gravel pit is located in the Missouri River bluffs in South Omaha, Nebraska. Here the Aftonian beds are typical, and in the western part of the pit the underlying Nebraskan drift is distinct. The workmen have penetrated into the latter about 16 feet.

Above the Aftonian there are about 8 feet of Loveland and 8 to 12 feet of loess.

In the southeastern part of the pit, which is the only fossiliferous part, 8 to 15 feet of Aftonian sand and gravel are exposed, and above these is a very prominent layer of Loveland 30 feet thick.

At other points in these bluffs Kansan till is very distinct between the Loveland and the Aftonian.

The following fossils were obtained from the Aftonian:

Elephas imperator, part of molar.
Equus ——, fragment of molar.

21. *Gladwin section*.—This is located in the east half of section 35, township 71 north, range xliii west, and its position has been described by Calvin.[18]

Here, in a bed of Aftonian silt, a complete set of upper and lower left

[18] Bull. Geological Society of America, volume 20, p. 344.

molars and premolars of *Equus scotti* was found by Mr. Gladwin. (For figure see ibid., plate 17.)

22. *Mad Creek section.*—In this connection it may be of interest to note the discovery of a fossiliferous bed of Aftonian in the eastern part of the State of Iowa. This exposure is located on the east side of North Mad Creek, in the northern part of Muscatine, Iowa, and was examined by the writer in company with Professor Witter. Here a bed of typical Aftonian sand and gravel (chiefly the former), about 25 feet in thickness, rests unconformably on a bed of Nebraskan drift and is separated from it by a strongly oxidized ferruginous band.

The greater part of the Aftonian consists of cross-bedded sand, but near the top it contains a layer of gravel about 1 foot in thickness, from which the late Professor F. M. Witter obtained a fragment of a molar of *Elephas primigenius.*

Overlylng the Aftonian is an irregular, slightly pebbly, reddish layer which is probably Loveland. It may, however, belong with the next superimposed stratum, a reddish joint clay which closely resembles a late or post-Illinoisan joint clay which is not uncommon in this vicinity. In either case there is no doubt that the sands and gravels are Aftonian.

Unidentifiable fragments of shells of mollusks were also found in the sand.

It will be seen that in the great majority of these fossiliferous sections the silt, sand, and gravel beds are clearly below the Kansan, while in several they are shown to be above the Nebraskan. Even in those cases in which some of the members of the typical section are wanting, the sand and gravel beds occupy a consistent position with reference to the members which are present. Moreover, it should be borne in mind that throughout the territory herein considered many more non-fossiliferous exposures of similar beds occur, and that these, too, are uniformly consistent with the fossiliferous beds in both structure and position. Again and again the writer has seen non-fossiliferous beds of sand, gravel, and silt lying unconformably between distinct Kansan and Nebraskan drift, thus multiplying the evidence of stratigraphic position furnished by the fossiliferous beds and leaving no doubt as to their horizon.

Are the Fossils Aftonian?

Some question may also arise as to whether the fossils really belong to the Aftonian or were derived from other formations. Fossils from older formations are sometimes found in the Aftonian, as they are in the drifts, and a similar origin might be suggested for the fossils herein discussed.

However, the excellent preservation of the fossils, especially the delicate mollusks, their distribution and abundance, the occurrence of parts of the same skeleton (as in the Akron and Wilkenson sections) in such position that some of the ligaments must have been present when deposition took place, and the fact that the same fossils have not found their way into the drifts, and moreover are not known from any clearly older horizon, all give strong testimony that the fossils are really of Aftonian age.

Conclusions

The following conclusions are based on the field studies here recorded:

1. The silts, sands, and gravels under discussion are interglacial and Aftonian.

2. The Aftonian is widely distributed in Iowa and adjacent territory and is especially prominent in western Iowa and eastern Nebraska.

3. The fauna of the Aftonian, both mammalian and molluscan, terrestrial and aquatic, indicates a comparatively mild climate during that period.

4. The presence of both the large land mammals and the terrestrial mollusks shows that large land areas were exposed in the vicinity of the flooded streams, which evidently transported and deposited the Aftonian sands and gravels.

5. While the Aftonian mammalian fauna has become extinct, the molluscan fauna, so far as it has been observed, has remained unchanged to the present day.

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SOME MINERAL RELATIONS FROM THE LABORATORY VIEWPOINT[1]

BY ARTHUR L. DAY

(Presented in abstract before the Society December 30, 1909)

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PURPOSE

Rocks have come to their present condition as the result of profound changes in physical structure and in the physical and chemical relations

[1] Manuscript received by the Secretary of the Society April 11, 1910.

of the component minerals. They therefore offer for investigation a number of problems of broad scope, requiring for their solution not only the application of the principles of geology, but also of physics, chemistry, and allied sciences. The problems are also complex in detail and do not admit of satisfactory analysis without correlating a great variety of evidence, both from the field and from the laboratory. The field evidence was, of course, the first to be sought; forces had to be recognized before they could be measured; but, having been identified, the next step is to seek to establish their relation to each other in the laboratory and to make use of the evidence from experiment for further and more accurate field studies.

Until recently, petrologists have confined their attention largely to the collection and examination of the field and microscopic evidence bearing on the rocks and their mode of occurrence, while the more precise quantitative methods of attack have been slower in development and are only now beginning to be considered seriously. This is especially true of experimental evidence, and one of the chief purposes of this paper is to invite the consideration of geologists, or, more particularly, of petrologists to certain phases of the problem of rock formation as they begin to appear from the viewpoint of the laboratory investigator, in order that men who are at work with a common scientific purpose, but with widely divergent training, may cooperate more effectively, both in gathering and interpreting the data on which to build the quantitative science of petrology.[2]

It will be well to recall that the tendency of scientific effort for a half century or more has been very definitely in the direction of more intense specialization. With perhaps an occasional exception, the men engaged in different branches of science have not been working along convergent lines, but along divergent lines, which are now so far apart that individual workers in one field do not find it easy to use the tools of another, nor at once to estimate the scope or point the application of the facts and relations established with these unfamiliar tools. It therefore happens quite naturally, in entering a new field of investigation such as that lying midway between geology on the one hand and physics and chemistry on the other, that the individual chemist, physicist, or geologist should feel that

[2] George F. Becker has repeatedly directed attention both to the need and to the opportunity for such cooperation. With Barus and King, he planned the first physical measurements made in the U. S. Geological Survey in the early 80's, and when these were interrupted in 1892 through failure of appropriations, it was his vigorous and continued interest which finally secured the reestablishment of the physical laboratory in 1901 and brought to it additional support from the Carnegie Institution of Washington in 1904. The introduction of the quantitative methods of physics and chemistry in the service of geology is therefore very largely due to Doctor Becker.

his personal experience does not adequately cover the whole ground. Neither is it desirable, in view of the enormous scope and detail of information necessary to a working knowledge of one of these sciences, that the investigator attempt to add to that an equally competent working knowledge of one or both of the others. It is a question whether such an effort would not be as likely to decrease as to increase his productive efficiency. It is rather to be regarded as a favorable opportunity for closer cooperation between workers representing different standpoints, when new and large problems are to be undertaken which lie in fields intermediate between existing branches of science or research. Large problems of industrial development have been effectively solved in this way, and there appears to be no fundamental reason for discriminating between the processes of gathering data for the advancement of knowledge and gathering data for commercial exploitation. The breadth of knowledge required and the necessity for exact information is certainly no less important in the first case than in the second. In approaching new problems which are accessible on two sides, it would appear, therefore, that the time has now arrived for effective combined effort of two or more men with appropriate equipment, rather than that any one should undertake them alone.

The Geophysical Laboratory is organized on this plan. It appeared to be sufficiently demonstrated that a comprehensive study of rock formation involves not only geology and mineralogy, but also physics and chemistry. The attempt was therefore made to perfect a working organization of men familiar with the methods of research in use in each of these fields. As a working system this has been most successful. It is therefore time to offer some of the results of such cooperative effort for more general consideration in order that we may also cooperate to make the most profitable application of the data thus obtained and become more familiar with the direction in which such investigation is leading.

Some Reasons for accurate Laboratory Work

Laboratory research in the service of geology has been attempted before by a number of different men, but with many serious interruptions and changes of viewpoint. Barus, Becker, and King proceeded chiefly from the physical side; Lagorio and the French scientists from the chemical; Vogt, more recently, from the standpoint of modern physical-chemistry. Barus laid great stress on the necessity for exact measurements and trustworthy data which could be applied quantitatively, but he has had few followers in this direction. It is, of course, an open question, in entering a new field, whether progress is most effectively made by pushing forward rapidly with hastily gathered approximate data or by a slower procedure, with greater attention to the magnitude as well as the kind and direction of the forces operating. The first plan may, and indeed often has, led the investigator far astray; the second, with its slow advancement, taxes his patience as well as that of others who are waiting to make application of his results. Perhaps the choice should be left to the temperament of the investigator himself. Be that as it may, it has seemed wise, in organizing a permanent laboratory for the investigation of geophysical problems in a broad way, to adopt the slower procedure, on the general ground that the geologist who will use the data obtained by the laboratory will be unwilling to take the chance of being led astray by approximations, knowing that at the time when the approximations were made measured data could have been obtained with a little additional effort and the resulting confusion and revision of inferential conclusions avoided. Furthermore, errors in the investigation of minerals have the habit of becoming cumulative, and may very soon vitiate any kind of productive conclusion if allowed to remain large or if carelessly treated. The plan determined on was, therefore, to undertake a quantitative and thorough investigation of the properties of the chief component minerals and of the forces which are operative in rock formation, drawing on the resources of the exact sciences to any extent which might prove necessary. The present paper is devoted to the consideration of some of the phases of this problem.

Temperature Measurements are now Trustworthy and of adequate Range

The study of the crystallization of minerals from the magma has usually been begun by determining the melting or solidifying temperatures of the original component minerals on the supposition that the order of the melting points[3] and the character of those physical and chemical properties which can be studied in the vicinity of the melting point will provide one of the clues to the order of crystallization. Barus[4] recognized that the first step toward such a study was to provide an accurate high temperature scale in terms of which these melting temperatures could be ascertained and expressed, and to it he devoted several years of great activity. With the same purpose, five years of continuous study have been given to this problem in our own laboratory, and the results

[3] In the normal case of pure elements, or compounds, in equilibrium, melting and solidifying temperatures are identical. There are many apparent exceptions among the minerals, some of which will be treated on a later page.

[4] Bulletin No. 54, U. S. Geological Survey.

are just published.[5] As a result of these, temperatures in the vicinity of 1000 degrees centigrade can now be determined within 1 degree, and the probable error of temperature measurements does not exceed 2 degrees until 1600 degrees is passed. It is possible to continue such measurements beyond this point, but the uncertainty undoubtedly reaches 5 degrees at 1750 degrees, and perhaps 20 degrees or more beyond that. Such temperatures (above 1600 degrees) are rarely encountered in the operations more immediately concerned with rock formation, although the refractory oxides (CaO, MgO), when pure, melt far beyond 2000 degrees, and the determination of their properties, both alone and in certain combinations, has required occasional measurements in the region above 2000 degrees, with which we have encountered no serious difficulty. In respect of this absolutely indispensable factor in any quantitative study of mineral or rock formation, we are now assured of a scale of temperatures of sufficient range and accuracy to meet the most exacting requirement likely to arise.

Interpretation of Melting-point Data

On the other hand, the interpretation of melting temperatures when obtained is a matter about which still hangs a cloud of obscurity. On this subject the laboratory viewpoint has changed somewhat with increasing experience, and the changes affect the whole question of the experimental study of rock formation as at present understood.

In its first inception the original plan was to make a collection of typical minerals, as pure as possible, and to observe, on an appropriate thermometer, the temperature at which they appeared to melt. In so far as this procedure commended itself to investigators as simple, direct, and free from any probability of misinterpretation, it has proved disappointing and misleading, for the data gathered in this way have differed so widely in the hands of different observers, and even in the hands of the same observer at different times, as to lead us to consider most of the early observations uncertain and therefore untrustworthy.

The experience of the laboratory student is perhaps better calculated to provide an explanation of these differences than that of the mineralogist. To make the case as concrete as possible, I will therefore take the liberty to introduce some observations of these phenomena as they have been gathered in the Geophysical Laboratory from time to time.

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[5] Arthur L. Day and J. K. Clement: American Journal of Science (4) 26, 1908, pp. 405-463; Arthur L. Day and Robert B. Sosman: American Journal of Science (4) 29, 1910, pp. 93-161.

Individuality of different Minerals in Melting

The laboratory student, proceeding from the physical standpoint, recognizes melting as a "change of state" involving, according to accepted molecular theory, a complete change in the molecular structure of the substance. Such a change of state will carry with it various visible evidences of its occurrence, as, for example, the disappearance of crystalline structure; a change of density; a change in the electrical conductivity; a more or less sudden appearance of fluidity causing it to take the shape of the containing vessel; a change in the specific heat—in a word, there appears a more or less conspicuous discontinuity in all its physical properties. In respect of these outward evidences, different substances will obviously vary.

In pure diopside, for example, the crystalline structure disappears with considerable promptness at the moment of melting, while silica and the more acid feldspars are extremely slow in transition from the one state to the other. The density change accompanying the change of state in anorthite is small, while for albite it is relatively much larger. If we assume that the relative density of the cooled products offers an approximate measure of its magnitude, the density change from anorthite to its glass is but 2 per cent, while for albite it is five times as great. In a substance like ordinary borax, which will no doubt prove to have several analogues among the minerals, the density change proceeds nearly as far in the opposite direction, while among organic compounds many are found to undergo no measurable change in either direction. Pure sillimanite flows so freely at the moment of melting that in an oxyhydrogen flame the liquid mineral is freely blown about by the flame, while pure silica and the feldspars again offer no outward evidence of flow during the melting process. Some of the phenomena attending the change of state are accessible to established methods of observation, while others can not readily be detected by any method suggested by existing laboratory experience. There is therefore a certain amount of individuality in substances which is altogether characteristic, but which may render a particular method which has proved fully competent with one substance to be very inefficient when applied to another. Considerations like these not only increase the scope of the laboratory problem, but detract somewhat from its assumed simplicity. If we would determine the melting temperature, or change of state, of a great body of substances, *it is not merely necessary to be able to measure temperatures accurately and conveniently, but also to obtain sufficient knowledge of the individuality of the substances under investigation to enable us to be quite sure that the method employed for detecting the change of state when it occurs is an appropriate one for each particular substance.* By way of illustration,

ORTHOCLASE FRAGMENT BENT AT 1200° UNDER LOAD (20 DIAMETERS)

A cleavage crack (dotted) has retained its orientation, although the fragment is melted through. The melted (dark) material is not squeezed out or otherwise displaced by the bending more than the unmelted original orthoclase.

one instance may be cited. More than one observer has sought to determine melting temperatures by watching for the moment when the substance appears fluid and runs in the crucible, and measuring the temperature at which this appearance of fluidity occurs. Moreover, this method has served successfully for the measurement of melting temperatures of low-melting salts and of metals, and will serve again in the case of single minerals[6] whenever it can be shown that this appearance of fluidity occurs coincidently with melting; but it so happens that in minerals this does not always hold true. A number of minerals, like quartz and the feldspars, melt to form liquids which are so viscous[7] that they show little or no tendency to take the form of the containing vessel, even after melting is complete, and therefore give no evidence, to the observer who merely watches for the mineral to run, of the beginning of melting. In the accompanying photograph (plate 3) a crystal of orthoclase was bent with a wire when partially melted. The amount of bending is shown by the cleavage crack. Dark areas are already molten; bright areas unmelted crystals. It is obvious that the melted (dark) material is not squeezed out or otherwise displaced by the bending more than the unmelted original orthoclase.

To the research student who has become experienced in such phenomena this plainly indicates that the particular property chosen, namely, the appearance of mechanical fluidity after sufficient heat has been applied, is not a suitable one with which to determine the melting points of substances which form viscous liquids, and that his ingenuity must devise a more appropriate means with which to approach these substances. In other words, experience teaches him that he must have more than one method at his disposal for the determination of melting points of minerals if he would obtain a competent record, and that he must make a study of each mineral from this viewpoint in order to assure himself that the method which he uses will locate the desired point without ambiguity in each individual case. In our experience, some minerals have been found to melt sharply to a thin liquid, and with these almost any method is competent to determine the melting temperature. Others can be more readily determined by noting the disappearance of crystal structure (indicated by abrupt changes in some optic property like birefringence) when a fragment of the mineral is observed in a furnace mounted on the table of a microscope. With still others the melting

[6] It will not serve for the study of a mixture of minerals, and is therefore of little or no value in approaching the subject of rock formation.

[7] Hyperviscous fluids differ essentially from solids. A fluid, unless extremely undercooled (glasses), yields continuously, though sometimes very slowly, even to the smallest pressures. A solid does not.

point can best be found by locating the temperature at which the latent heat of fusion is absorbed or released.

Uncertainty of Solidification—Undercooling

Let us carry the examination of the properties of different minerals somewhat further. We may undertake to determine the melting temperature of a particular mineral, and may obtain, as we suppose, a competent measurement, but on cooling again we note that the solidifying temperature falls at some distance below the melting temperature. From the petrological standpoint, the solidifying temperature will perhaps appear the more important of the two, and proceeding from this viewpoint alone, if these two temperatures should differ in the same substance, we might be tempted to reject the former and adopt the latter without special endeavor to obtain corroborative evidence of the significance of the difference. But here again we may mislead ourselves by an over-hasty conclusion. Laboratory experience has also shown us that minerals in which the solidifying point falls at a different temperature from the melting point, also display considerable differences between successive determinations of the solidifying point if the rate of cooling is changed or if the mineral, while melted, happened to be heated high above its melting temperature before cooling. In the explanation of this phenomenon there is valuable information for the student of mineral crystallization, if he will take the trouble to seek it; for it appears that minerals, much more than metals, possess the kind of molecular inertia by virtue of which changes of molecular arrangement, such as melting or solidifying, take place with some difficulty and slowly, instead of promptly and regularly, as metals do. Accordingly, as the liquid mineral cools down to its melting temperature, it may not crystallize at once, and, delaying, may cool for a considerable distance into the unstable region below the melting temperature before crystallization begins. Even after it has begun to crystallize the process may proceed so slowly, while the temperature continues to fall, that the visible evidence of a crystalline condition may not appear for some time longer. In such a mineral, obviously the crystallizing temperature is a property which can be determined only by the most careful observation, if at all. In all the pure minerals so far studied in the Geophysical Laboratory it happens that it can not be determined at all[7a]—that is, minerals, when cooling under atmospheric pressure, do not crystallize promptly at a particular temperature which is constant and charac-

[7a] Since the text of this article was written, accurate measurements of chemically pure pyrrhotite (by E. T. Allen) show the temperature of crystallization to occur promptly and to be identical with the melting point.

teristic of the substance, but at random, the temperatures being dependent on the rate of cooling and various extraneous conditions which need not be recounted here. It is even possible that such a substance, when cooled rapidly, may be so inert with respect to changes of molecular arrangement, or so viscous, that it may cool far below the melting temperature, becoming more viscous all the while, until finally it reaches the temperature of the room without having crystallized at all. Such substances are not uncommon; they are known, both to physics and to geology, as glasses, and they possess no molecular arrangement characteristic of the quasi-rigid condition which they appear to have reached. Strictly speaking, therefore, from the physico-chemical standpoint, such substances are undercooled liquids, and are still in an unstable condition, albeit opposing with overwhelming inertia (viscosity) any molecular rearrangement whatever. Proof of this lies in the fact that the latent heat of fusion which was absorbed during melting, and which is an absolute concomitant of the change of state, is not released on cooling to glass. In this condition days, or years, or even geologic time, may conceivably elapse before the characteristic crystal forms appear. In the extreme case where the crystallizing force encounters resistance of overwhelming magnitude, crystal formation is no doubt permanently stopped until new forces or conditions intervene to bring relief. Ordinary window glasses, or the obsidian cliffs of the Yellowstone Park, offer familiar illustrations of such permanently interrupted though still incomplete operations.

Some Difficulties of Interpretation where Glass is Present

The physicist, therefore, soon learns that there is much individuality among the characteristic properties of different minerals, and that determinations of their physical constants must proceed with unusual caution lest the result be misleading. In particular, having established the fact that many minerals do not solidify (crystallize) regularly at definite temperatures, he must, not always, perhaps, but usually, depend on melting-point determinations if he would learn the normal temperature of their change of state. He is also forced to take into account the fact that the phenomenon of melting does not have the same appearance with different minerals—that some change more conspicuously in one property, some in another—and that his observation of the moment of melting must be made with proper respect for the individual characteristics of the particular mineral under investigation. If a mineral has been found to melt to a viscous liquid, he may not set up a thin sliver, as was the common practice a few years ago, and observe with a telescope the first appearance of rounded corners as a criterion that the melting point had been reached. It may have been passed long before. Furthermore, with respect to this particular illustration, if he has had wide experience he may reason that crystallization represents the operation of a force of characteristic magnitude operating between the molecules to maintain a given systematic arrangement (crystal form), while the rounding of the corners of a thin fragment represents the tendency of all molecular systems to reduce to the form which has the smallest surface—that is, a sphere. Bearing in mind that the effect of such a surface tension will be greater the smaller the sliver and the sharper its corners, without regard to its melting temperature, it will be conceivable that the rounding of the edges, which he has arbitrarily determined upon as his criterion, may represent the prevailing of one internal force over another, in which the observed temperature bears no relation to the melting point or change of state whatever.

The classic experiments of Barus to determine the change of density of a mineral upon solidification offer another illustration of the difficulty of determining the physical constants of minerals which cool to glass with little or no crystallization. All of his observations (save one) were made on cooling diabase, and he has left an unqualified record that the melting rock cooled to glass without crystallization in each case. There was therefore no discontinuity of molecular structure, no characteristic change of properties, no release of the latent heat of fusion—in short, no solidifying point whatever on the cooling curve, and therefore no temperature at which observations of density would have significance to the student of rock formation.[8]

Their Effect upon the early Measurements

All these observations of the peculiar properties of individual minerals in the vicinity of their melting temperatures which have been revealed by laboratory study subtract something, it is true, from the value of existing records, in obtaining which it is known that certain necessary precautions, of which an outline has been given above, were not recognized, and therefore not taken, but on the other hand they add immensely to our knowledge of the behavior of minerals during the process of crystallization, and offer positive reasons, where none existed before, for some of the anomalous observations which have been made on natural rocks, from

[8] The properties of mineral glasses were wholly unstudied at the time when Barus's experiments were made, but the sudden change in density, amounting to 3 per cent, which he obtained, is not explained by any known property which they have been found to possess.

which it appeared that the order of crystallization as seen under the microscope was not always the same, even though the chemical composition was approximately so. It is also possible for the first crystals which separated to redissolve at lower temperatures, so that the cold rock does not necessarily contain in itself a complete history of its crystallization. Such physical conditions as rate of cooling and the presence or absence of nuclei about which crystals might begin to form enter into this problem as determining factors. It is probably unwise, at this early stage in the development of the subject, to draw sweeping conclusions from these relations, except, perhaps, to emphasize the fact that the order of crystallization or differentiation from the magma will hardly be determined on the basis of chemical composition alone, though of course it must be fixed by the law of minimum potential.

Can trustworthy Melting Temperatures be obtained?

It remains for us to pursue the question on its constructive side, and to inquire whether trustworthy melting temperatures can be determined for the minerals in the face of the limitations which many of them have been seen to possess. Obviously not by the simple and heretofore generally acceptable process of using the same subjective criterion of the moment of melting for all minerals alike; namely, the change in the appearance of the mineral in a crucible during heating. Between the latitude which can be allowed to the judgment of the observer and the wide difference in the properties of the different minerals themselves, this method will fail, as it has done heretofore, to yield uniform and therefore trustworthy results on which to base serious geological conclusions. On the other hand, if we choose for each mineral an appropriate property which shows a conspicuous change corresponding to the change of state, or, still better, if we leave the personal judgment of the observer out of the question entirely, at least wherever it can be done, and measure by a sensitive method the change in the energy content of the system which is invariably coincident with its change of state, whatever the external evidence of the latter may be, we shall arrive, with nearly all the minerals, at perfectly definite constants, which may be redetermined at will, and which always possess physical significance.

Assuming that we have reached this standpoint, that the individual limitations in the properties of the minerals must be respected and that the judgment of the observer must be confined to conspicuous properties, or, still better, wholly eliminated, the analysis of melting-point determination becomes a straightforward question which can be treated along recognized lines.

Other Minerals lower the Melting Temperature

Most of us are familiar with the typical eutectic diagram as it appears in the text-books of physical chemistry and in the newer treatises upon rock formation (Vogt,[9] Iddings,[10] Harker[11]). This diagram tells us plainly that if to the component mineral (A) of simple and definite composition with a definite melting point (*a*) we add a small quantity of another mineral (B) (which forms no appreciable solid solution[12] with it), this melting temperature will be measurably lowered (to *b*), and a sufficiently large addition will bring it down to the lowest point of the curve which, following the physical chemists, we have come to call the eutectic (*c*). If our first mineral (A) is pure wollastonite, and we add 5 per cent of pure diopside (B), the melting point is lowered from 1510 degrees (pure wollastonite) to 1502 degrees. If more is added until the mixture contains 60 per cent of diopside and 40 per cent of wollastonite, the mixture will crystallize as a eutectic (*c*) at 1348 degrees (see figure 7, page 172). This is perhaps not the time nor the place for a long physico-chemical discussion of the conditions of vapor tension in a solution which result in the lowering of the melting point when one substance is mixed with another and melted. It can be found, with numerous illustrations, in any text-book of physical chemistry. The illustrations are drawn for the most part from the study of aqueous solutions at low temperatures, but

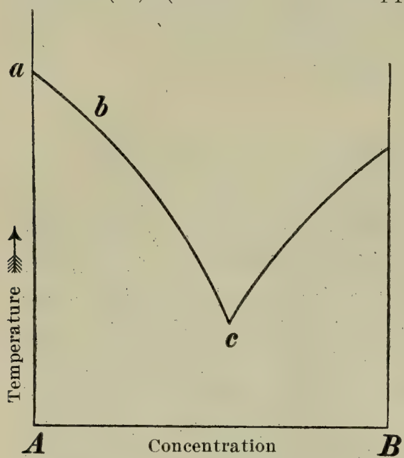

Figure 1.—*Diagram showing Temperatures of Melting and Solidification in a Eutectic Series*

[9] J. H. L. Vogt: Die Silikatschmelzösungen (2 vols., Christiania, 1903-'4); Physikalisch-chemische Gesetze der Krystallisationsfolge in Eruptivgesteinen, Tscherm. Min. u. Pet. Mitth., 24, 1905, pp. 437-542; 25, 1906, pp. 361-412.

[10] J. P. Iddings: Igneous rocks, 1909.

[11] Alfred Harker: The natural history of igneous rocks, 1909.

[12] Some minerals are able to take up a very limited quantity of another ingredient in solution so intimately that the second invariably crystallizes out with the first like an isomorphous pair (page 167), in which every crystal unit contains both minerals. Such crystals are called "mix-crystals" and such a solution *after crystallization* a "solid solution." When saturated in this way, its further behavior is independent and normal.

the quantitative studies of mineral solutions so far undertaken in the laboratory have brought to light no serious exception to these qualitative generalizations.[13] Quite the contrary. The enormous increase in the range of temperature required for mineral investigation compared with low-melting salts has afforded most satisfactory and greatly desired confirmation of the general validity of these relations.

Pure Types are Necessary

Without entering on a discussion of the principle itself, therefore, its applicability will be immediately obvious. If the addition of one mineral to another in any quantity, however small, lowers its melting temperature, and the amount of the lowering is considerable, this may be another thread which leads directly to the situation described earlier in this paper, namely, that mineral melting points gathered from all sources exhibit differences sufficiently large to make them wholly untrustworthy. Any change in the composition, even if small, places the melting point on a sliding scale of temperature so steep (the curve *ac,* figure 1; also AB, figure 7) that considerable differences in the measured melting points must inevitably result. Such observations reflect only too faithfully the fact otherwise established in many different ways, that typical minerals are not found without small and variable admixtures of other minerals which affect their melting temperatures differently. This is in no sense a limitation on the study of the characteristics of minerals during formation, or the competence of such studies, undertaken in the vicinity of the melting temperature, to reveal their true relation, but it imposes on us the absolute necessity of first establishing some quantitative relation between the *kind and amount of impurity and the kind and amount of effect produced by it.* To a certain extent also we may determine relations between some natural types (like eutectics) which have important factors in common, but we can not recognize and quantitatively establish the interdependence of those qualities which determine types if they can not first be separately observed. To the laboratory student this is merely a particular case of the general working rule that the number of unknown factors in his system must not be greater than the number of measurements available for their determination. He is undertaking to determine not only the character of the operative forces in rock formation, but their

[13] It is perhaps well to warn the student against the mistake of trying to apply to rock formation the *quantitative* laws of solution which have been deduced for very dilute *aqueous* solutions, and which can not yet be applied to concentrated aqueous solutions, much less to viscous concentrated silicate solutions, at least not until the various participating factors have been definitely evaluated, which has never been done.

magnitude, and to do this successfully requires that each variable shall be capable of independent determination. Without these precautions it will be impossible even to distinguish those forces and components which are essential from those which are merely incidental to his problem.

Preparation of pure Minerals

This conclusion might perhaps have been reached *a priori,* but in common with many conclusions of like fundamental significance it has waited to be brought out by a long and painful experience of experimental disappointment. But our attitude toward the new science must be constructive, and not destructive. If the accumulated experience of years has gone to demonstrate that quantitative experimental petrology depends on obtaining the minerals separately—that is, chemically pure—and determining their individual and characteristic properties, and afterward on our ability to combine them in known relations, the question which presses hardest for answer is obviously whether or not chemically pure minerals can be obtained for laboratory study by practicable processes. To this most vital question all the experience thus far gathered by the Geophysical Laboratory goes to establish the affirmative answer. Not much is to be expected from a more diligent search for purer natural types than those already gathered; neither is there much encouragement for the successful purification of natural minerals by laboratory process with the single exception of quartz, but mineral synthesis from chemically pure ingredients has been almost uniformly successful.

Here again the difficulties encountered by the laboratory in the synthetic preparation of minerals contain information for the student of natural formations. Not all molten minerals, as we have seen, can be made to crystallize within the limited time available in the laboratory. Such important minerals as quartz and the alkaline feldspars will not crystallize in a furnace at any temperature unless volatile ingredients are present to give the required molecular mobility, and thus to facilitate molecular rearrangement. With the help of such volatile constituents, pure quartz crystals can be obtained of a size and perfection sufficient for determinations of high accuracy. It therefore suggests itself quite naturally that we are approaching rather than departing from natural processes in crystallizing quartz out of a solution containing volatile ingredients which participate in the formation process, but do not appear in the finished product. There is abundant field evidence that vein quartz has at some time possessed mobility sufficient to enable it to penetrate into the minutest cracks, and yet but insignificant traces now remain of any other components. This same vein quartz, when melted in the laboratory, is among the most viscous of minerals, and takes the form of the containing vessel only when placed under stress. It is, therefore, more than probable that it once contained ingredients which contributed enormously to its fluidity during solidification, but of which only a trace is left—that is, volatile ingredients, like alkaline water solutions, or fluorine; the same materials, in short, which produce the same result in the laboratory.

Another difficulty arises through the tendency of rapidly crystallized laboratory products to come out in a cryptocrystalline condition. If the short time interval available for laboratory experiments is insufficient to provide opportunity for the formation of large units, may it not also be true that the size of grain in natural formations gives some indication of the rate at which the formation went on? An inference of this kind must, of course, be applied with care if volatile ingredients are present, for small differences of composition often produce relatively very large differences in the fluidity of the magma, and therefore in the size of the crystal grains. In fact, the introduction of volatile ingredients is the expedient used in the laboratory production of minerals which tend to crystallize only in the most minute units.

As a record of laboratory experience, it is unnecessary to do more than call attention to the character of these difficulties which the preparation of the pure minerals in the laboratory encounters, and to say that none of them has yet proved insuperable. Nearly all our publications contain illustrations of the practicability of obtaining pure mineral types of sufficient perfection for competent study. Given these pure types, and there is no difficulty of principle in establishing properties and relations and erecting on them a quantitative system of solutions corresponding to the typical natural rocks. In practice, the development of such a system is slow, for the number of participating components in natural rocks is very large, and the complications accordingly intricate. The solution of the difficult cases must await the gathering of a wide range of laboratory experience and a considerable elaboration of existing theory. On the other hand, the attempt to build a physico-chemical system on observations of natural minerals alone will surely resemble an attempt at triangulation without fixed triangulation stations.

All governing Conditions must be known

If the first essential to the successful study of the properties and relations of the minerals in the laboratory is the ability to obtain pure types, the second is certainly the necessity of defining the conditions under which these types shall be examined in the vicinity of their formation temperature. Here the experience of the laboratory points out two situations which lead to confusion. The first is the fact, not hitherto mentioned, that the addition of impurity, even of minute proportions, to a pure mineral not only has the effect of displacing its melting point, but also of stretching it out along the melting curve in such a way as to conceal its exact location upon the temperature record of the thermometer. The second is the frequent difficulty in establishing equilibrium during the operation under investigation.

Melting "Points" and melting Intervals

Among the somewhat voluminous records of mineral melting points which have come out of European laboratories in recent years, one feature has reappeared persistently, namely, the inability of the observer to fix upon a single temperature for the melting point of a mineral under observation; instead, he almost invariably finds and attempts to fix the boundaries of a melting interval, often of 30 or 40 degrees (actually 50 degrees in the adjacent feldspar curves (figure 2) measured in this laboratory), throughout which the phenomenon of change of state appears more or less continuous. Physical and physico-chemical experience offers reasons for this behavior which may in part explain, but which do not always help to remedy the difficulty. If the material under investigation is a solid solution or isomorphous mixture (as in the feldspars), we know that the phenomenon of melting includes a continuous change of composition which is actually distributed over a considerable range of temperature, so that the appearance of slow melting is not here misleading, but is the correct record of its actual progress. The true relations here require to be ascertained by establishing, either through chemical analysis or the microscopic examination of a thin section of the material after solidification, the order in which the crystals of different composition have formed and the limits of variation in their composition.[14]

If, however, the substance under investigation is a chemically pure compound the composition of which does not change during the change of state, the reasons for the change being distributed over a temperature interval are of a more accidental character, and should in most cases be capable of elimination by careful study. Suppose, for example, we ex-

[14] The general cases of this kind (see also page 166), together with various exceptions encountered in the study of the feldspars, were discussed, both from the practical and theoretical standpoint, in the record of the first investigation made in the Geophysical Laboratory, from which figure 2 is taken. (The Isomorphism and Thermal Properties of the Feldspars, Publication No. 31, Carnegie Institution of Washington.) The discussion is too long and too severely physico-chemical for reproduction here.

amine the distribution of heat in a crucible containing a pure mineral whose melting point requires to be determined. In a cylindrical furnace in which heat is supplied to the charge from the sides (the usual case, figure 3) its outermost layer will be the first to receive heat, and through this layer heat will be transmitted to the inner layers somewhat slowly, for most minerals conduct heat but poorly when compared with familiar metals. The same analysis shows that heat leaves the crucible for the

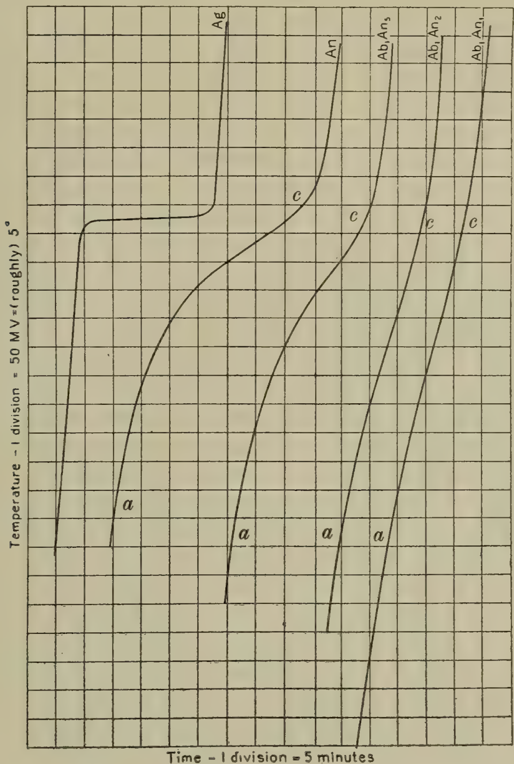

FIGURE 2.—*Melting Curves of the Feldspars*

Taken from Day and Allen: "The Isomorphism and Thermal Properties of the Feldspars." Publications of the Carnegie Institution of Washington, No. 31. The melting intervals are (roughly) included between the letters *a c* of each curve. A typical metal melting curve (silver) is included for comparison.

most part through the top and bottom layers in the same order. At the beginning of melting around the periphery, therefore, the center of the charge has a lower temperature, and has not begun to melt. The exposed upper surface is colder still. If the material has a very high melting point these gradients may be steep. Suppose that we have decided not to depend on the appearance of the exposed surface in the crucible, and are working with a closed furnace and a sensitive thermometer imbedded in the charge which will record the temperature of the portion of the charge in contact with it; melting will then begin in the outermost layers (figure 3), and will proceed gradually toward the thermometer at the center. Here the temperature record will show heat absorption from the beginning to the end of the melting process, but only the melting of the innermost layer which is in immediate contact with the thermometer gives the true melting temperature of the substance. Such an observation gives the appearance of a melting interval where none really exists. It can be avoided by simply omitting the outer layers—that is, by using a much smaller quantity of material in the form of a narrow cylindrical charge. If, instead of using a crucible of conventional form, we reduce the amount of material to 1 or 2 grams in a crucible about the size and shape of a lead pencil, and of perhaps 1 inch in length (figure 4), the same melting point, which appears much displaced and distorted upon its curve in the large crucible, will appear and reappear with the most satisfactory sharpness with the small one, with the added advantage that the experimental operations all become much simpler. By this simple expedient measurements of the melting temperature of pure diopside have been repeatedly made which agree within 1 degree at 1,391 degrees.

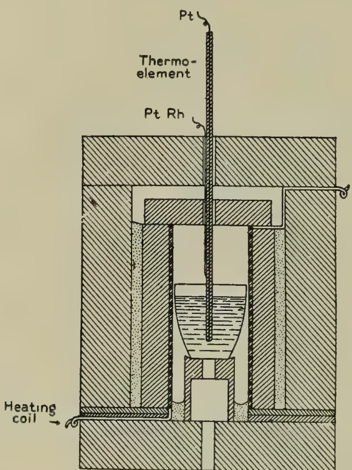

FIGURE 3.—*An Electric Furnace of usual Type with Crucible and Thermoelement in Position*

Substantially the same effect is produced by the presence of a small amount of impurity. Traces of heat absorption, indicating the beginning of the change of state, appear on the heating curve far below the melting temperature of the pure substance, owing to the solvent action of the impurity and consequent change in the specific heat of the mixture. This disturbing effect may be serious, or it may be insignificant, depending on the thermal properties of the substances involved, their amount, and mutual solubility. If the amount of impurity is very small (a few tenths of a per cent), the absorption of the heat of fusion will proceed rapidly to a reasonably constant maximum, the interpretation of which will not be difficult after a few trials with widely different rates of heating. Very rapid heating minimizes the apparent disturbance, but may (in viscous substances) superheat the whole charge. Small and narrow crucibles (figure 4) have the effect of diminishing this difficulty also. This whole question of apparent anomalies in the determination of melting points due to small quantities of impurity and irregular heat distribution has been treated in considerable detail, both theoretically and practically, by W. P. White in two recently published papers.[15]

The third difficulty with the sharpness of melting points is inherent in the participating materials themselves, and the temperature-measuring device is merely offering a faithful interpretation of what actually occurs.

Figure 4.—*Small Crucible for the accurate Determination of the Melting Point of Minerals (nearly full size).*

Earlier in the paper it was noted that a liquid mineral on cooling often does not crystallize promptly, but through the influence of other properties, chief among which is the viscosity, the crystallizing temperature is lowered by an uncertain amount. This was explained as a kind of molecular inertia, inherent in certain substances, through the operation of which any molecular rearrangement, such as crystallization from a molten mass, is seriously hindered. Now it sometimes happens that what is true of crystal formation in a cooling mass may also be true of crystal destruction in a melting mass—the crystalline structure can only be broken down with considerable difficulty and delay. In such a case the expenditure of the energy required to break down the molecular system (latent heat) will in fact be distributed over a temperature interval, and will be so recorded by the thermometer. Just as in the case of the delayed solidification, where the solidifying temperature appeared low and variable with the rate of cooling, so here the delayed melting may result in too high a temperature, which is equally dependent upon the rate of heating. In extreme cases, of which quartz and albite again serve as familiar examples, this effect is so pronounced that no melting "point," in the proper sense of the word, can be obtained—that is, the change of state itself actually extends over a greater or less temperature interval, and the accurate interpretation of such a melting curve is a matter of some uncertainty. A series of actual curves showing the long temperature interval (100 to 200 degrees) over which the heat absorption of melting orthoclase is distributed, with different rates of heating, is shown in figure 5. The dotted line indicates the interval during which heat is absorbed. In

[15] W. P. White: Melting-point determination. American Journal of Science (4), 28, 1909, pp. 453-473. Melting-point methods at high temperatures. American Journal of Science (4), 28, 1909, pp. 474-489.

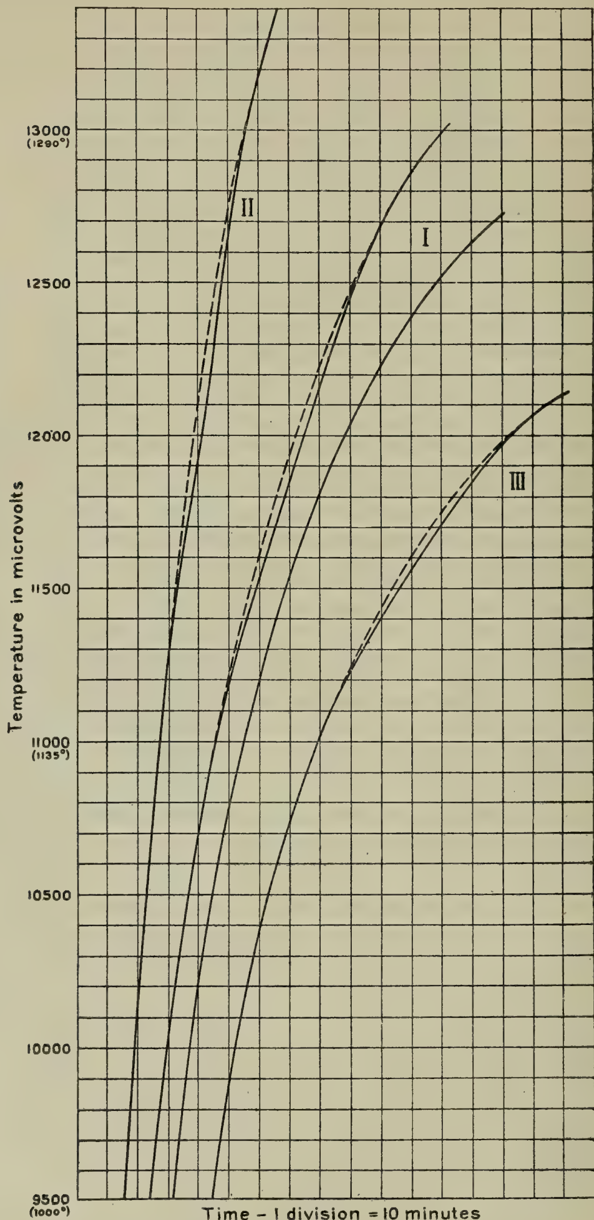

FIGURE 5.—*Melting Curves of Orthoclase*

The area included within the dotted line represents the approximate distribution of the latent heat of fusion for different rates of heating. (From Day and Allen, loc. cit.)

such cases equilibrium[16] is not established during melting or solidification, and no "point" can be found which possesses greater physical significance than any neighboring point. To assign especial significance to any single temperature is, therefore, wholly arbitrary. If the interval is short, its limits can be determined approximately; if long, there is little of physical fact with which to determine them accurately.

Significance of "Equilibrium"

The uniform experience of the laboratory has been that where equilibrium can be established during melting or solidification—that is, where the molecular system is not too inert to react with reasonable promptness to changes of temperature and pressure—there is a melting temperature which is constant for the particular substance, which is absolutely characteristic of that substance, and which can be determined. Such a melting temperature is independent of the rate of heating and of other superimposed conditions. On the other hand, there are minerals (of which quartz and albite were cited as examples) of such molecular inertness that they do not reach equilibrium in the time available for a laboratory measurement, and can not be made to do so unless the volatile ingredients which must have participated in their natural formation can be restored.

Effect of Pressure

A number of experiments have already been undertaken in the laboratory which serve to show that such a restoration is entirely practicable, and which incidentally show the operating forces of nature's laboratory in a more normal relation to each other. The field is not yet sufficiently developed for more than a suggestion of the conditions which prevailed in nature during the cooling of mineral masses containing volatile components in solution, but the suggestion is worth noting. To the petrologist seeking to obtain exact information upon the behavior of his minerals during heating and cooling, it has been somewhat puzzling to learn from the laboratory that pure silica is not known to melt below 1600 degrees, while his field observations clearly show that most observed natural quartz must have crystallized considerably below 800 degrees. It has been equally

[16] By equilibrium is meant the situation in which all the operative forces so balance each other that the system would remain indefinitely exactly as it stands, provided no change is made in the pressure or temperature or composition. As soon as equilibrium is established, physical measurements can be made with certainty and intelligently interpreted. Measurements made in transition periods under indeterminate conditions are very difficult to interpret at all.

puzzling to the laboratory student to hear the petrologist ascribe the low formation temperature and several physical characteristics of rocks to the effect of pressure, when he knows that pressure has relatively little effect upon a single pure mineral at any stage in its formation process. Thirdly, as has been noted before, the laboratory observer reports that liquid silica and many acid silicates are enormously viscous, while the field observer finds abundant evidence of extreme fluidity during their crystallization in nature. All three of these difficulties of deduction become clearer immediately we take into account the effect of volatile ingredients. The melting temperature, as we have seen, is much lowered by such substances, the viscosity is enormously reduced by them, and finally, the pressure is necessary to hold these volatile ingredients in solution. The very fact that the pure silica of the laboratory, or a pure natural silica, behaves in a way so different from the obvious behavior of the same substance during its initial crystallization in nature is of itself proof that its behavior has been influenced by the action of other substances, and if these are no longer present, or have left mere traces, we must assume that they were volatile and endeavor to restore them. This is the next step in the laboratory problem, and one in which supporting field evidence will be of the greatest assistance.

Single Minerals—Summary

In the preceding pages the effort has been made to describe some of the properties of single minerals near their melting temperatures as they have been developed by laboratory study. It has been more or less inevitable that emphasis should be laid on what may be called the disturbing elements like the effects of viscosity in preventing the establishment of equilibrium during the change of state, and so delaying, or even preventing, crystallization from the liquid, in concealing the outward evidence of melting, or in producing cryptocrystalline masses. The effect of small amounts of impurity in lowering the melting temperature and preventing the accurate interpretation of melting-point determinations and the effect of the relatively poor heat conductivity in causing considerable local irregularities of heat distribution in the mineral under observation have been frequent causes of misunderstandings and misinterpretation in laboratory study. Little has been said of the successful work of Barus and others in establishing the temperature scale which is absolutely indispensable to any quantitative research in this field.

It has been shown that these difficulties which have been encountered by the laboratory have merely served to develop important phases in natural rock formation, and are, therefore, an essential part of the problem. The disappearance of the volatile ingredients from extruded magmas has left them viscous and caused obsidian formations. Their presence lowers the formation temperature, gives mobility to the fluid magma and larger individual crystals. It is through the effects produced by the volatile components also that one of the chief effects of pressure as a controlling force in rock formation has been brought to light; the pressure serves to retain the fugitive ingredients in the rocks, and these are probably chiefly responsible for the low formation temperatures. No doubt the field experience of the petrologist will suggest to him many other relations which result from the same causes.

Mixtures of Minerals

It now remains for us to consider mixtures of minerals from the laboratory viewpoint. Given a homogeneous mixture of two minerals in the molten condition, contained in a suitable crucible, and suppose them to be in complete equilibrium for the prevailing temperature. We will also suppose that neither of the components will boil within the temperature range of investigation, and therefore that the effect of pressure is insignificant and negligible. If this mass is gradually cooled, a temperature will soon be reached when the solution will contain more of one of the ingredients than it can hold in equilibrium. Now, whether it will crystallize or not will depend primarily upon two opposing forces, the power of the molecules to arrange themselves in the order characteristic of the particular mineral now in excess, and the power of the viscosity or some other opposing property to prevent this or any other rearrangement, exactly as in the case of a single mineral. If the viscosity prevails, the tendency of the excess component to crystallize is not strong enough to overcome the opposing force, crystallization is delayed, or maybe indefinitely deferred, and the excess component cools without displaying any evidence of its relation to the rest of the solution, for viscosity increases as the cooling goes on, so that if the excess mineral does not crystallize at an early stage it may find no better opportunity farther down. Thus our whole solution may cool gradually from its initial temperature to the temperature of the laboratory, without anything whatever happening within it to distinguish one component from another or the whole mass from any other mass of random composition. The solution merely persists as a liquid (glass) beyond the temperature where the ingredients should separate, and reveals none of its characteristics.

The eutectic Relation

The second possibility when the cooling solution reaches the temperature where one component is in excess has not yet been definitely proved to exist among the minerals, but it has been studied by Miers and Miss Isaac[17] with a view to such application, and is included in all the major treatises[18] on physical chemistry, with a variety of illustrations from aqueous solutions at low temperatures. According to this view, although one of the minerals is now in excess and free to crystallize out, the equilibrium is of a metastable or neutral kind, so that the actual crystallization of the mineral can only be precipitated by introducing solid crystal fragments of the same mineral (or another isomorphous with it) from without. These fragments, which may be minute in magnitude and few in number, provide the crystal nuclei about which the molecules of the excess component immediately group themselves. No other variety of crystal or any form of mechanical disturbance will cause the separation. The range of temperature over which this attitude of indifference to all but its own kind obtains is relatively small and differs for different substances. After passing through this metastable region the excess mineral enters a region of labile equilibrium where crystallization of the unstable component may be expected to be rapid and spontaneous, and to continue in step with the cooling until the eutectic temperature is reached. Here the other component is due to crystallize side by side with it, and will do so unless delayed for a longer or shorter time by similar limiting conditions.

In practice, at high temperature it is difficult to distinguish this case from the preceding one (see Harker, loc. cit., page 209), where crystallization is merely delayed by viscosity or some form of molecular inertia. Of course, the same situation may equally well arise among pure minerals crystallizing alone.

The third possibility is the normal one in which one component begins to crystallize out the moment the cooling has reached a point where it is present in excess, and equilibrium prevails throughout the whole process of crystallization. The eutectic also appears promptly, and the entire operation follows the simple diagram on page 152. Curiously enough, no

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[17] Miers and Isaac: Journal of the Chemical Society (London), Transactions, 89, 1906, pp. 413.

Miers: Science Progress, 2, 1907, pp. 121. (Also several other papers.)

[18] The best statement of this case is by Ostwald: Studien über die Bildung und Umwandlung fester Körper: 1, Übersättigung u. Überkaltung, Zeitschr. f. phys. Chem., 22, 1897, pp. 289.

certain case of this most formal type of crystallization has yet been established with certainty among the minerals. As in the case of a single mineral cooling down after melting, there is always *some* undercooling[18a] from one or other of the causes above outlined, and crystallization is more or less delayed. It is, however, altogether probable that the basic minerals which are more thinly fluid will furnish numerous illustrations of it.

It is not necessary that the reader infer from the absence of explicit cases of normal behavior in the crystallization of mixtures of pure minerals so far studied that we are on the wrong track, and that the existing theory of solutions and the phase rule can not be properly applied to mineral solution, for the converse case of a mineral mixture melting normally has been frequently observed and is unmistakable. The eutectic usually melts promptly for all compositions in which it is present in sufficient quantity for observation, while the excess component enters the solution gradually, and disappears at the temperature appropriate to its concentration. It is a matter of great good fortune to the investigator endeavoring to establish quantitative relations between the minerals, that although individual physical properties frequently intervene to prevent the normal phenomena from appearing promptly on the *cooling* curve, the *heating* curve is rarely disturbed by them.

In this connection, attention may again appropriately be called to a phenomenon first mentioned in a publication from this laboratory on the crystallization of feldspars,[19] in which it was pointed out that in viscous solutions which are not stirred, rapid heating, and even more conspicuously heating but a short distance above the melting temperature, frequently affects the behavior of the solution during subsequent cooling. When crystals are melted, their molecules frequently remain in the same relative positions in the liquid, "as motionless as a school of minnows in a brook,"[20] for some time, and for a considerable temperature interval (a hundred degrees or more) above the point where melting is complete. In time and at high temperatures the schools are scattered, but recrystallization on cooling is much assisted if the cooling takes place before these schools have become dispersed.

Of course, the number of such individual mineral characteristics or properties which enter into the quantitative determination of its relations to other minerals in the laboratory is greater for a two-component system

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[18a] See footnote [7a], page 148.

[19] Arthur L. Day and E. T. Allen: Isomorphism and thermal properties of feldspars. Publication No. 31, Carnegie Institution of Washington, p. 54.

[20] As Doctor Becker first suggested to me.

than for a single mineral, and much greater when three components are brought together; but they have not been found to differ in character from those offered by way of illustration in the preceding discussion of the behavior of a single mineral when heated. Their increased number invites caution and greatly enhances the value of laboratory experience in prescribing the conditions which shall surround the measurements, but they are in no sense prohibitive, nor do they threaten to become so. Beyond this their elaboration is more properly left to discussions of particular cases in which they occur, of which the literature of the Geophysical Laboratory already contains several.[21]

The Isomorphous Relation

The crystallization of a two-component mixture in which the component minerals are in isomorphous relation to each other is of somewhat different character. Here, again, the general case may be found in any desired detail, and with appropriate illustrations in general treatises on physical chemistry and in the more recent handbooks of petrology (Iddings, Harker—loc. cit.); also in the publications of Vogt (loc. cit.), Doelter,[22] and the Geophysical Laboratory.[23] Some particular phases of the subject are brought out by laboratory study which do not immediately appear in the investigation of natural minerals with the microscope, and there is little in the low temperature researches of the physical chemist to suggest looking for them. The cooling of an isomorphous mixture of definite proportions (for example, a lime-soda feldspar), even in the simplest case of unlimited mutual solubility and no intermediate compounds, offers at least two cases which the petrologist will find it necessary to differentiate—the case in which under-cooling occurs, and one in which it does not. If under-cooling does not enter (the simplest theoretical case), a solution of A and B (figure 6) of composition *a*, cooling from a molten condition to the temperature represented by *b*, begins to separate at once, but not in crystals of one of the original components, as in the case of a

[21] Day and Allen: Isomorphism and thermal properties of the feldspars, loc. cit.; Arthur L. Day and E. S. Shepherd: The lime-silica series of minerals, American Journal of Science (4) 22, 1906, pp. 265-302; E. T. Allen, Fred. Eugene Wright, and J. K. Clement: Minerals of the composition $MgSiO_3$; A case of tetramorphism, American Journal of Science (4) 22, 1906, pp. 385-438; E. T. Allen and J. K. Clement: The role of water in tremolite and certain other minerals, American Journal of Science (4) 26, 1908, pp. 101-118; E. T. Allen and W. P. White: Diopside and its relations to calcium and magnesium metasilicates, American Journal of Science (4) 27, 1909, pp. 1-47; E. S. Shepherd and G. A. Rankin: The binary systems of alumina with silica, lime, and magnesia, American Journal of Science (4) 28, 1909, pp. 293-333.

[22] C. Doelter: Physikalisch-chemische Mineralogie, Leipzig, 1905.

[23] Day and Allen, loc. cit.

eutectic pair. The first crystals to appear are of mixed composition, somewhat richer (*cd* in the figure) in the higher melting component (A) than the original composition, and the remaining solution is in consequence left somewhat poorer in this component. These first crystals will be followed by others containing less and less of A than *cd,* until the mixture finally ends its crystallization with mixed crystals of a composition well over toward B. In the figure, the lower curve represents the composition of the crystals which form, and the corresponding points (found by drawing horizontal lines through the points desired) of the upper curve, that of the solution left behind. It is a process in which the compositions change continuously throughout, and obviously the heat distribution also. There is, therefore, no sharp melting or solidifying point. Whether the resulting crystals will vary continuously in composition from *c* to *e,* or will appear in broad or narrow bands with insignificant transition stages, or will even come out homogeneous and of composition *f,* will depend in part upon the characteristic properties of the ingredients and the nature and extent of the disturbances to which the cooling system is subjected. All these cases are fairly common in igneous rocks. It should be borne in mind, however, that if the solution is of a character to follow promptly all changes of pressure and temperature as they occur, no bands will appear. The appearance of bands is direct evidence of slow transitions and disturbed conditions of cooling; their common occurrence in the rocks is indicative of frequent and considerable interruptions during the cooling process.

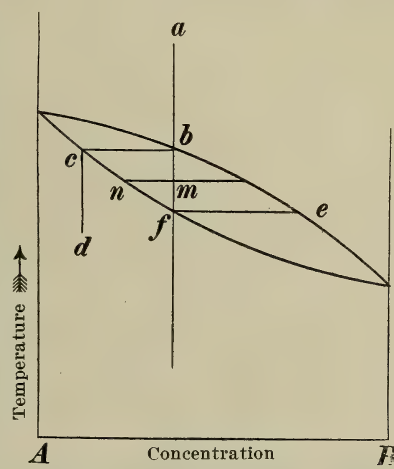

FIGURE 6.—*Diagram showing Change in Composition during Melting in an Isomorphous Series*

If under-cooling occurs, no crystals separate when the solution reaches the temperature *b,* but cooling continues along the line *bf* for a greater or smaller interval, as the case may be. If it were to begin crystallizing at *m,* the process would be exactly the same as before, except that the range of possible compositions would be smaller—that is, there would be no crystals as high in (A) as in the previous case (the first crystals would have the composition *n*). If the solution reaches *f* or cools below it, without the formation of any crystals, it will crystallize (if at all) in homogeneous mix-crystals of that composition. This was the case with all the lime-soda feldspars crystallizing in the laboratory. Crystallization did not begin until the molten mass had passed entirely through the region in which the changes in concentration occur, and all the crystals and the glass residue, if any was left, were of one concentration, corresponding to that originally taken. We made no effort in this investigation to produce the banded structure in imitation of nature, on account of the time required to do it and the fact that it would add but little to our knowledge of the subject. All that is necessary is a furnace in which the temperature can be held constant within the temperature region where the changes of composition occur and sufficient patience to wait for the results (with the intermediate feldspars, probably some weeks).

Simple Mixtures—Summary

These simple cases, very briefly stated, serve to illustrate the behavior of cooling mixtures of two components. In the first case (the eutectic series) one of the components first appears separately, followed by a mixture of both in fixed proportions, called the eutectic; in the second (the isomorphous series), the two components always appear together, the first crystals to form being usually considerably richer in the higher melting component, followed in gradually changing proportions by the lower melting mixtures. Both these cases may occur in the same series of mixtures. For example, if the metasilicates of lime and magnesia be mixed together in a number of proportions and studied after the manner outlined above, it will be found that a compound (diopside) forms in the middle of the series. On one side, this compound forms a simple eutectic series with pseudo-wollastonite; on the other, a partial series of mix-crystals with the magnesian metasilicate. It is not uncommon to find two or three compounds forming between two components, with an appropriate number of eutectics between. Lime and silica, for example, yield two compounds, a metasilicate and an orthosilicate, and eutectics occur between pure silica and the metasilicate, between the metasilicate and the orthosilicate, and finally between the orthosilicate and pure lime. In this last series (orthosilicate-pure lime), not only both components, but the eutectic itself, melt at temperatures above 2000 degrees.

Molecular Composition at the Moment of Crystallization

There is opportunity, in a series like this, to study a situation to which Harker has called attention especially, namely, that the molecules of the liquid magma are not the simple oxides (SiO_2 and CaO), but are silicates of a composition appropriate to the percentages present in the solution

($CaSiO_3$ and Ca_2SiO_4), except near the ends of the series, where the pure oxides remain over in excess. If combination occurred only at the moment of crystallization, the accompanying energy change would be of a different order of magnitude, according as the component appearing in excess is one of the original oxides or one of the silicate combinations.

Characteristics of the cooled Products—some Definitions

The next important step, after differentiating the various situations through which a cooling magma passes, is to learn to recognize the distinctive characteristics of the products which result—the glasses, isomorphous mixtures, eutectics, and new compounds.

Up to the time of Lagorio but little attention was paid to the glasses in the study of rock synthesis. Lagorio endeavored to make use of them as hypothetical standard solvents in which various oxides could be dissolved to form rocks of different character, making it the counterpart in the mineral world of water in aqueous solutions. Each rock was to be considered as a mineral or group of minerals in solution in one of two common solvents. This viewpoint laid much emphasis upon the importance of rock glasses, but it has not yet contributed materially to the elucidation of rock formation. Doelter has endeavored to ascribe individuality to glasses, and has experimented with a great many glasses of different compositions without arriving at any conclusion of general interest. Barus, in his determinations of physical constants, esteemed it a matter of secondary importance whether a mineral cooled to a glass or crystallized. Modern physical chemistry ascribes little individuality to glasses as such, but considers them merely as under-cooled liquids which can be crystallized only with the greatest difficulty, or not at all, and which in consequence possess only tentative and general properties. They accordingly possess about the same significance as any other incomplete reaction which is caught in transition between states. It is much more important to be able to define these end states and their relations than to be able to fix the progress of the interrupted operation in individual cases. We find obsidians in which some crystallization has occurred, and rocks in which but a small portion of the total content is glass, all of which merely serves to show that the progress of individualization of a magma may be interrupted anywhere whenever the cumulative action of the opposing forces has reached a sufficient magnitude. It may also be resumed on the advent of new, favorable conditions, such as would be produced if a supersaturated magma were to come in contact with crystals of the excess component.

An isomorphous mixture, as its name indicates, is an intimate (crystalline, not vitreous) mixture of two or more component minerals in which the physical properties change continuously with the composition. Isomorphous mixtures are most commonly found between minerals of closely related atomic or molecular grouping—that is, of similar chemical composition or crystal habit. The concentration may vary slightly or considerably in the same hand specimen, depending on temperature or other changes during its crystallization. Its distinctive feature, which is familiar both to the field and to the laboratory student, is the *continuity* of the changes of its physical properties with the changes in percentage composition of its ingredients. It may be added, for the sake of clearing up a possible misunderstanding, that the term "solid solution," as defined by the physical chemists, applies to *crystalline* solutions of this kind, and not to the glasses, as is sometimes stated. The glasses from this viewpoint are still ultra-viscous liquids, and retain the "latent heat of fusion" which would have been given off had a change of state occurred.

The eutectic is a mixture in which the component minerals bear a definite relation to each other, but neither loses its identity. It must not be regarded as in any way analogous to a compound. It has been commonly supposed that the simultaneous crystallization of two minerals in eutectic relation always resulted in a peculiar close-grained interweaving of the crystals to which the name "eutectic structure" has been applied. Such a "eutectic structure" is usual in metallic alloys and is readily identified, but pure minerals cooling under laboratory conditions do not show it. Whether the peculiar interweaving observed in graphic granite is a true eutectic structure of quartz and feldspar, or merely another of the effects of an earlier intermixture of certain volatile ingredients no longer found there, can not receive a positive answer. Such laboratory experience as we have appears to indicate that this structure is the result of a much more complicated activity than the mere cooling of quartz and feldspar in eutectic (?) proportions. The appearance of a eutectic in a solution of two minerals can be recognized in a variety of ways, but it is extremely doubtful if any *structure* has yet been found to be *characteristic* of the eutectic relation between minerals.

The appearance of a compound in a series of mineral mixtures breaks up the series abruptly into two, either of which may possess any of the characters above outlined. These may be treated quite independently of each other for purposes of systematic study of any kind. The compound possesses independent physical and chemical properties which can be determined for the purpose of distinguishing it from all other compounds, *provided* it can be separated out and independently studied. The mere appearance of particular optical properties in the grains of a rock section, for example, while it may suffice for the immediate identification of a known mineral, is not sufficient for the establishment of a new one, A compound must be separated for purposes of definition. New compounds are not uncommon products of the laboratory study of minerals at their formation temperatures. Many of these are high-temperature minerals (like pseudo-wollastonite) which have no counterpart in the natural rocks. Had the natural rocks crystallized without water or low-melting alkalies, we should no doubt have had them, for some of them crystallize with great promptness from appropriate compositions, and are perfectly stable over considerable ranges of (usually high) temperature.

Eutectics in complicated Mixtures

We have no trustworthy examples of the behavior of complicated mineral mixtures in eutectic relations under known formation conditions, but a brief consideration of the subject from the theoretical standpoint indicates the probability of certain complications in the consideration of two or three component eutectics in the presence of other soluble minerals. With but two pure minerals present, the eutectic appears as the intersection of two curves, and is a point (B, figure 7)—a single mixture in definite proportions. With another mineral present which is soluble in all proportions in both, the eutectic point (with its two minerals separating side by side) becomes a line along which the concentration varies, and (presumably) the structure also. If a fourth mineral is added, its geometrical representation in three-dimensional space becomes difficult, but it is easy to see that the system must have received another degree of freedom, and that the eutectic (still considered as between the two original minerals, but in the presence of two others) is now freely variable in its own composition. In a four-component system, we may have two minerals separating side by side over a range of concentrations and temperatures. It is, of course, conceivable that this divariant system might look more or less like the so-called (!) eutectic structure, though it might separate from very different initial concentrations. To ascribe particular structures to the influence of two or three component eutectics in rocks which contain other minerals, and which very probably contained more volatile constituents during formation, is therefore a somewhat hazardous undertaking at the present stage of development of the subject.

An Illustration of a cooling Mixture

Suppose we now examine the behavior of a cooling mineral mixture in a simple actual case.[24] If we take the mixture of calcium and magne-

[24] We have encountered no actual case in which no undercooling occurs; all the temperatures here given were, therefore, determined from melting material which is simply the converse case of the one here described. The description of the order of phenomena is somewhat clearer in this form.

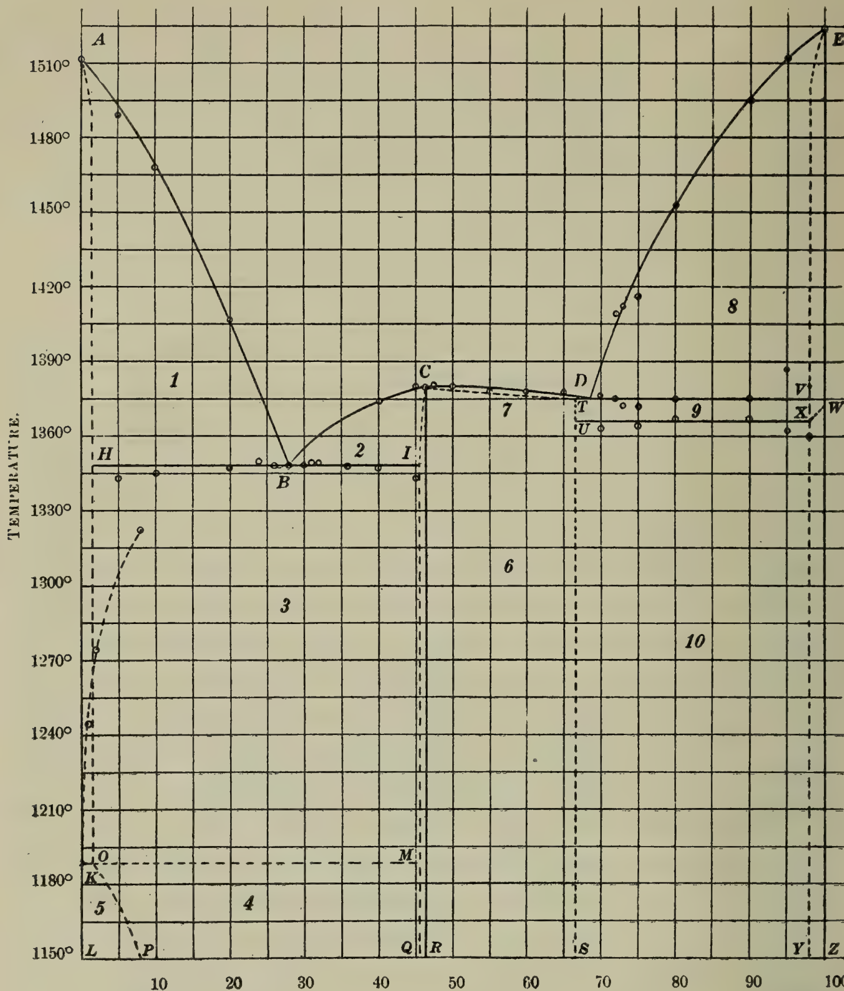

FIGURE 7.—*Diagram showing the Relation between Calcium Metasilicate and Magnesium Metasilicate when mixed in any Proportion at any Temperature*

Principal Areas of the Diagram

1. AHB α-$CaSiO_3$ + liquid.
2. BIC Diopside + liquid.
3. HIMO α-$CaSiO_3$ + diopside.
4. OPQM β-$CaSiO_3$ + diopside.
5. KOPL Mix-crystals diopside in β-$CaSiO_3$.
6. CTUSR Mix-crystals of $MgSiO_3$ in diopside.
7. CDT Mix-crystals of varying composition + liquid.
8. DEV α-$MgSiO_3$ + liquid.
9. TUXV α-$MgSiO_3$ + diopside mix-crystals.
10. UXYS β-$MgSiO_3$ + diopside mix-crystals.

sium metasilicate mentioned above, and suppose it to have been melted and thoroughly mixed in the proportion of 80 parts $CaSiO_3$ to 20 parts $MgSiO_3$ (figure 7), and then to be gradually cooled preparatory to observing solidification, we shall encounter not one change of state only during the cooling, but three, each of which is definitely characterized by a change in the energy content of the system, and is therefore a physical discontinuity which completely defines the stability of the substance with respect to temperature, provided only we are in position to make an intelligent interpretation of what occurs. To follow this case, the first release of heat on cooling appears at about 1405 degrees, and represents the temperature at which, if no disturbance of the equilibrium takes place, the excess of calcium metasilicate begins to crystallize out. At about 1350 degrees, calcium metasilicate and diopside will crystallize in eutectic mixture with a second release of heat. From this point downward all of the solution has become a solid mixture of these two ingredients, but at about 1190 degrees, if the mechanical forces which oppose any rearrangement of the molecules be not too great, the calcium metasilicate will go over from the crystal form known as pseudo-wollastonite into true wollastonite with a heat change similar to the two preceding, but smaller in magnitude. The melting of this mixture is exactly the reverse process. If the original mixture had contained only 10 per cent of magnesium metasilicate instead of 20 per cent, all the other conditions remaining the same, crystallization would have begun when the solution reached a temperature of 1465 degrees instead of 1410 degrees, the other two changes following as before. With a still smaller percentage of magnesium metasilicate, the first crystals might have appeared as high as 1500 degrees.

The same two ingredients in the proportions $CaSiO_3$ 47, $MgSiO_3$ 53, would have given but a single change of state (the melting or crystallization of pure diopside), while with $CaSiO_3$ 20, $MgSiO_3$ 80, three changes of state would have occurred as in the first instance, except that the excess component which first appears is now α-magnesium silicate instead of the corresponding lime compound, and the inversion which follows is an enantriopic change in the magnesium silicate.

If the above explanation has been clear, it offers an illustration not only of the crystallization of an excess component, but of the eutectic and a subsequent inversion of one of the components of the eutectic. It illustrates also the continued lowering of the melting temperature of one mineral ($CaSiO_3$) through the addition of increasing quantities of another mineral. This concrete illustration is quite typical of the general case, in which the solution of one silicate in another will lower its melting point, not by one degree or two, but by 10, 20, 50, or 100 degrees, oftentimes according to the character of the added mineral and the amount of it which is present.

The adjoining figure (figure 7) representing the complete determination of mixtures of calcium and magnesium metasilicates contains several illustrations of all the features described.

Adding a third mineral to the first two will not only still further lower the melting temperatures, but will increase the number of phases and eutectics to the point of seriously complicating their interpretation. To disentangle such a group of phenomena from the appearance of the mixture in the furnace while the changes are going on is quite out of the question.

Incomplete Reactions

In concluding the discussion of those minerals whose properties are difficult to establish because of their failure to respond promptly to changes of pressure or temperature, attention should be directed to the extreme case, which also is by no means uncommon. If nature has succeeded in crystallizing certain of her most common minerals only through the presence of volatile ingredients, and sometimes not at all (the Obsidian Cliffs) when none are present, she has quite as often paused in the transition from less stable to more stable solid forms. Even qualitative experiments with the blowpipe have developed a great number of cases of instability due to incomplete reaction. One has been worked out in detail in this laboratory. Two forms of magnesium metasilicate have been found which are more stable than enstatite; one has been identified in the Bishopville meteorite, which is supposed to have encountered a very high temperature; the other has never been found in nature. Even before this relation was established, Vogt advanced the hypothesis with a considerable degree of positiveness that all the natural amphiboles represent unstable forms or the incomplete development of the corresponding pyroxenes, and there are many cases of this kind. The minerals which have segregated from the magma have come out step by step in one combination or another, and in one crystal form or another, in obedience to a definite system of transformations, following definite relations of pressure, temperature, and composition. Such a series of transformations may have reached complete stability at the temperature and pressure now prevailing, or it may not. There is a time factor which obtains in all reactions, and it by no means follows, as we have frequently seen, that because geologic time is reckoned in large intervals, sufficient opportunity has been given for all mineral reactions to become complete. If a mineral appears in excess in a cooling solution, and may take a stable or an unstable form, the unstable form will appear first,[25] and may go over into the stable form afterward, or may not, according as favorable conditions happen to occur or not. Enstatite is a familiar case of an unstable mineral which has probably never attained its stable form except in the laboratory.

The Application of Van't Hoff's Law—Vogt

The most comprehensive attempt to apply these principles of solutions to the crystallization of igneous rock magmas is unquestionably that of Professor Vogt, of Christiania. He employed for the purpose a series of artificial slags out of which he was able to crystallize most of the ordinary constituents of the basic igneous rocks, and the results of his experiments are in reasonably close analogy to the crystallization of these rocks except for the volatile constituents, and the absence of these is probably a sufficient explanation of the absence of those minerals which are missed from his series, such, for example, as the alkali feldspars, hornblende, muscovite, and probably quartz. Vogt's investigations were along two principal lines. He sought to ascertain what mineral first crystallized from a solution of given composition, and, second, whether the lowering of the melting point through the addition of one component to another in such a magma follows the Van't Hoff-Raoult law.[26] In pursuing the first inquiry, he was able to establish for most cases that the first mineral to separate is the mineral in excess of the eutectic proportion. This is the more noteworthy in view of the fact that Vogt made no special effort to obtain or study pure minerals, and his results are therefore wholly qualitative in character. The second investigation, Part II of Vogt's principal memoir, did not result in equally definite conclusions. He was able to establish the fact that the addition of one mineral to another or to a definite mixture of minerals, in general lowers the melting point, as we have just explained, but he was not able to offer satisfactory quantitative evidence of the amount of this lowering. This may have been due to two difficulties:

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[25] The demonstration is given in Ostwald, loc. cit.

[26] J. H. Van't Hoff: Die Rolle des osmotischen Druckes in der Analogie zwischen Lösungen und Gasen. Zeitschr. f. phys. Chem., 1, 1887, pp. 481—.

J. H. L. Vogt, Der Silikatschmelzlösungen, II, 1904, p. 128. Vogt applies the law in this form:

$$t = \frac{m}{M} \cdot \frac{.02\ T^2}{q}$$

T = absolute temperature of the melting.
t = amount of lowering of melting temperature.
q = latent heat of fusion per gram of solvent.
M = molecular weight of the dissolved substance.
m = concentration.

(1) the effect of the foreign minerals known to be present which directly affected the relation which he sought to establish; (2) the somewhat unsatisfactory character of his temperature and calorimetric measurements. Then, too, the Van't Hoff-Raoult relation owes its derivation to the gas laws, and has been found to hold by analogy for aqueous solutions up to concentrations of 1 per cent, but not for any others. It is therefore a serious question whether the analogy can be strained to cover the most concentrated and complicated silicate solutions as Vogt has tried to make it. Furthermore, none of the constants of Van't Hoff's law except the temperature have been determined for definite silicates. For these reasons the determinations of the eutectic percentages of orthoclase and quartz, of anorthite and diopside, of diopside and enstatite, and so on through a considerable list, are not satisfactory. Except for the quantitative relations, for which he hardly possessed adequate data, Vogt has shown in a most comprehensive and suggestive way that the laws of solution apply directly and very generally to silicate solutions, and that the relations of the minerals in the rocks can be determined if the necessary measurements can be made at the temperatures where the formations occur.

Summary and Conclusion—The geologic Thermometer

Briefly reviewed, the laboratory situation, then, is this: True characteristics of mineral types can not generally be obtained from natural specimens containing the usual quantity of foreign admixtures. If we are to triangulate our field by the use of mineral types, which would appear to be necessary in whatever light their relations be viewed, we must, therefore, use pure minerals for these types. It has been sufficiently demonstrated that such pure types can be prepared, and with them all the necessary physical characteristics determined. In the discussion of mineral melting temperatures, we differentiate two classes of minerals: (1) those which can be depended on to give a definite point of change of state independent of the experimental conditions which are provided (that is, which remain in equilibrium throughout), and (2) a group of minerals in which the molecular deorientation corresponding to the change of state is so much hindered by viscosity or similar retarding influences that there exists no particular temperature at which the change will be found to begin, and no particular range of temperature or time interval within which it will proceed to completion. This is a property of this group of substances, and not a limitation of the methods of examining them. Theoretically there is a temperature limit up to which the solid is stable, and above which melting will begin and proceed indefinitely, if sufficient time is given. Conversely, there is a theoretical upper limit to the beginning of crystallization. Practically the beginning may be delayed and the rate variable without limitation, and the assignment of boundaries to the melting interval be therefore wholly arbitrary. The manner of participation of such minerals in rock formation, either in nature or in the laboratory is usually dependent upon the presence of certain volatile ingredients (mineralizers?) which, even when present in very small quantities, appear to increase the molecular mobility of the mineral to an extraordinary degree, and thus to enhance its activity greatly. In dealing with minerals of this class, the duty of the laboratory is clearly to follow nature by replacing those volatile ingredients of which insignificant traces are still found in most of the mineral deposits, and to establish with equal care the progress of the reactions in their presence.

What has been said of the melting temperature is true in somewhat less degree of the inversions of solid crystalline minerals from one crystal form to another. It happens that the energy required for such transformations is relatively small compared with that required for melting, and so but few such have hitherto been discovered. The application of methods of great precision in the Geophysical Laboratory has developed a number of these where none were suspected before, and therefore greatly enriched our knowledge of the development of individual minerals at relatively low temperatures. Furthermore, many of these transformations occur so punctually at a characteristic temperature as to serve an unexpectedly useful purpose in the establishment of a system of geologic thermometry.

In a number of recent publications in this laboratory, the behavior of quartz has been cited in illustration of the facility with which geologic temperatures can be established through the agency of such transformations. We are now able to differentiate sharply, for example, between quartz formed above 575 degrees and quartz formed below that temperature; and this, in turn, is radically different from the cristoballite, which forms above 800 degrees. In each of these cases unmistakable records have been left on the minerals themselves of the transformation through which they have passed. Several other such inversion temperatures are known for the minerals already studied, and together they form the beginning of an accurate system of temperatures of which immediate and extensive application can be made in the study of natural rocks.

The problem of building up a geologic thermometer is a straightforward one. We must select those substances which respond promptly to changes of temperature, and determine for these the temperatures of their changes of state. It may happen that a given mineral will offer but a single reference point of this character, or, like quartz, a single mineral may yield four or more sharp physical changes which recur promptly at the appropriate temperatures. In our experience it has happened that inversions, or changes of crystal form in the solid state, occur more promptly and are often more definitely recognizable than the melting temperature, even though the quantity of energy involved in the inversion is considerably less. Furthermore, inversion temperatures are much less dependent upon volatile constituents. Pure quartz, for example, melts very slowly over a long range of temperature. Its crystallization does not occur under laboratory conditions without the assistance of volatile substances. On the other hand, its inversion at 575 degrees takes place sharply under the thermal microscope, with never a delay greater than .5 degree, either on the heating or the cooling curve. Wherever such transformations, which are known to occur promptly at a particular temperature, leave an intelligible record behind, we have an absolute bench-mark in geologic thermometry, and the establishment of a sufficient number of such will place in the hands of the geologist a temperature scale of universal application. Nearly every mineral studied yields one or more such points, and hardly more than a beginning has yet been made in this field.

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BEARING OF THE TERTIARY MOUNTAIN BELT ON THE ORIGIN OF THE EARTH'S PLAN[1]

BY FRANK BURSLEY TAYLOR

(*Presented in abstract before the Society December 29, 1908*)

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INTRODUCTION

One of the grandest facts which the science of geology has established up to the present time is the existence of a great world-belt, or girdle, of Tertiary fold-mountains almost encircling the earth. This mountain

[1] Manuscript received by the Secretary of the Society October 4, 1909.

belt comprises the entire Pacific coast of the two Americas and of Asia and extends westward along the southern border of Asia and Europe to the Atlantic coast in Spain and Morocco. In the Malay archipelago the belt branches to the eastward and sends an arm around the northern and eastern sides of Australia, but the mountain ranges of this branch are mostly submerged, and are now represented only by island chains, including New Guinea, New Caledonia, New Zealand, and many smaller islands. Excepting the gap between New Zealand and southern Chile, the Pacific Ocean is completely surrounded by the Tertiary mountain belt. This fact rests upon a sound basis of observations, and is one of the most comprehensive and deeply significant things which mankind has yet learned with certainty concerning the development of the earth. The Tertiary mountain belt is a large element in the earth's plan, and a satisfactory explanation of its origin is a desideratum of the first order.

Under the various forms of the contraction hypothesis of mountain making, this mountain belt has been ascribed to horizontal thrust movements directed from the ocean toward the land. The cause assigned is subsidence of the earth segment which underlies the ocean—a consequence following, according to some, upon secular cooling and contraction, and this has been the dominant view; but upon planetesimal settling and solidification, with some cooling and contraction, according to others, and upon original differences of density, with molecular changes and expansion, producing deep-seated movements from the oceans toward the continents, according to still others.

The remarkable relation of the Tertiary mountain belt to the Pacific Ocean is the thing which is usually most emphasized in discussing the origin of these mountains, and principles based on the supposed meaning of this relation have been applied to other mountains as well, for it is claimed that the relation indicates an oceanic cause which is general in its application. But the fact should not be overlooked that this same mountain belt forms an important part of the periphery of all the continents excepting Africa, and since the belt as a whole falls naturally into divisions or parts corresponding to the several continents to which it has peripheral relations, the question arises as to whether these parts may not be causally related to their associated continents rather than to anything in the oceanic areas.

The several continental divisions of the belt show characters which seem to correspond roughly to continental magnitudes. For example, Asia, or, more accurately, Eurasia, with small parts of northern Africa and Alaska, stand together structurally as one continental unit and constitute by far the greatest of the continental bodies. Asia proper is the main, central part of this vast crustal sheet, but even this part alone is considerably greater than any other continent. The peripheral mountain ranges of Asia show prominently certain forms—chiefly curved, arc shapes—which are scarcely recognizable or are generally inconspicuous in the peripheral ranges of the other continents. The mountain ranges and plateaus of Asia are greater in every way than those of other continents—greater in areal extent, in height, mass, and breadth of plan. It is a question to be determined whether all these distinguishing attributes are not due mainly to the fact that Asia, considered as a dynamic unit of the earth's crust in the process of diastrophism or mountain making, is larger—greater in extent and mass—than any other similar unit.

If a crust-flake, like that which we call Asia, should move a given distance as a unit, it would certainly produce greater results in crustal deformation than would arise from the movement of a flake having only one-tenth of its magnitude, and the difference in the results would be still greater if the larger flake moved several times farther than the smaller one. The products might differ not merely in magnitude, but to some extent in kind also. Australia is a continent of the same type as Asia, but it is relatively feeble in its development; its peripheral ranges are relatively weak. They are mostly submerged, and, so far as known, they show none of the peculiar forms which characterize the great peripheral belt of Asia.

Figure 1 shows the location of the Tertiary mountain belt. Later researches seem to suggest some slight additions in eastern Asia and in the western and southwestern Pacific, but these are welcome changes and are not discordant.

The mere existence of this vast mountain zone encircling the earth is of itself a remarkable thing, but its significance is prodigiously increased when the distribution and age of these mountains are taken into account and when some of their structural or tectonic relations and characteristics are analyzed. The entire belt is essentially of one age, all made or largely augmented within the limits of one definable and relatively short and recent period of geological time. Moreover, this period of diastrophism is the last or most recent of the great mountain-making epochs—the nearest to us in time. For this reason partly the mountains of this belt are all relatively young—so new that there has not yet been time for them to be destroyed or very greatly reduced by erosion. This is one of the chief reasons for their great height in many places and for the relative youthfulness of their physiographic expression. It is also a reason for the relatively unmodified state of the tectonic lines which they mark, for these lines have not been disturbed or disarranged by any im-

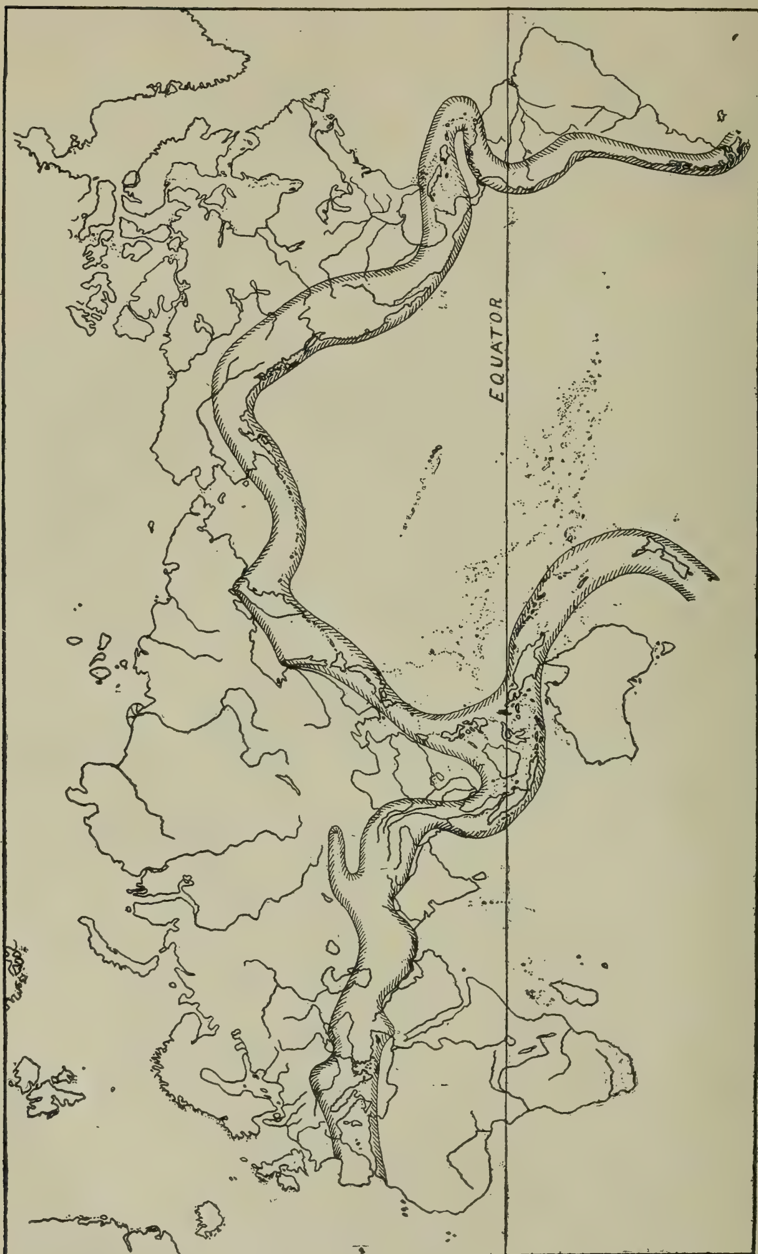

FIGURE 1.—*The World on Mercator's Projection*

Showing the distribution of the Tertiary mountain belt. (From the Berghaus Physical Atlas, 1892.)

portant mountain making of later date. They retain substantially unchanged the forms which Tertiary diastrophism gave them. Hence, whatever characteristics or peculiarities of form or plan mountain-making forces are wont to impress upon their products, these ought surely to be discernible in a mountain system which is at once the newest and most extensive upon the earth. Indeed, the Tertiary mountain belt stands out so prominently as the product of a recent, distinct, and apparently completed epoch of mountain making that within certain limits it can be studied by itself, without much reference to older mountain-making epochs.

It is admitted by all that the mountains of the great Tertiary belt, like the older ranges of fold-mountains, were produced chiefly by compressive forces acting in a horizontal direction, and that the total amount of compression involved is equivalent to many miles of horizontal movement of the earth's crust. What was the nature of those movements? In what direction did the crust move in producing the Tertiary mountains of Asia—from the ocean toward the land or from the land toward the ocean? This is the crucial point.

There is a considerable body of facts which bear strongly upon this question; a few of the more important are briefly set forth below in a discussion of the origin of the Tertiary mountains, and the conclusions thus reached seem to throw some new light on the origin of the earth's plan.

Suess' Interpretation of the Plan of Asia

In his great work, "The Face of the Earth," the eminent Austrian geologist, Eduard Suess, has devoted much space to the consideration of the continent of Asia. As a result of his extensive studies, Suess reached the conclusion that, in consequence of the cooling and shrinkage of the earth as a whole, all parts of the crust have settled or sunken down toward the center, the ocean basins most and the high continental areas least. A few quotations will show the general character of his conclusions. After noting the contrast between the outlines of the ocean basins and the structure of the continents, Suess remarks that "*these ocean basins are areas of subsidence*"[2] (II, 536). "As soon as we recognize the ocean basins as sunken areas, the continents assume the character of horsts" (II, 537). "*The crust of the earth gives way and falls in; the sea follows it.* But while the subsidences of the crust are local events, the sub-

[2] Unless otherwise stated, all quotations from Suess are from "The Face of the Earth," authorized English translation by Sollas. Reference is made to volume and page. All of the italics in the quotations belong to Suess. Four parts of "The Face of the Earth," in three volumes, have been published at the time of this writing.

sidence of the sea extends over the whole submerged surface of the planet. It brings about a general negative movement" (II, 537-538). All changes affecting the height of the sea at one time over the whole globe Suess designates as *"eustatic movements"* (II, 538). *"The formation of the sea basins produces spasmodic eustatic negative movements"* (II, 538). *"The formation of sediments causes a continuous, eustatic positive movement of the strand-line"* (II, 543). In other words, a sinking of the sea floor at any place lets the ocean down from its shores all over the earth, while the piling up of sediments in any part gradually raises the level of the whole ocean. In this way Suess accounts for some, but not all, of the ancient strand-lines now found above ocean level.

Referring to Asia and Eurasia, Suess defines their structure and growth in different words at different times, according to the various points of view from which he contemplates the subject. "Asia consists of an obstructive fragment of Indo-Africa—the peninsula of India— . . . and of a great piece of the earth's crust folded to the south. The folds, however, are interrupted and separated by platforms which lie between them like rigid blocks, although in the platforms themselves we may also recognize the traces of much older folding in the same direction" (II, 195). *"The whole southern border of Eurasia advances in a series of great folds toward Indo-Africa;* these folds lie side by side in closely syntactic arcs, and for long distances they are overthrust to the south against the Indo-African tableland" (I, 596).

Among the several continents Asia seems to afford the most perfect expression of Suess' idea. He describes the ancient "vertex," or central land of Siberia around which the rest of Asia, especially to the east, south, and west, appears to be arranged in roughly concentric zones. This relation finds its most prominent expression in the trend lines of the mountain ranges. The vertex occupies a large region lying chiefly north, northeast, and northwest of Irkutsk, in Siberia. The vertex itself is very old, being capped by horizontally bedded pre-Cambrian strata which appear to have suffered no notable disturbance since their deposition. The surrounding lands are disposed mostly in bands or zones of rocks of younger age, the nearest to the vertex being of Paleozoic age, followed farther out by Mesozoic, and lastly by Tertiary. Thus, going southward from the vertex, the mountain ranges are composed of successively younger strata folded and faulted by horizontal compression, until along the margin of the continent the peripheral ranges belong to the great Tertiary belt. Each belt of folded strata was subjected to horizontal compression in such a way as to make a mountain range usually in the form of an arc opening northward or toward the vertex, and roughly concentric with it.

That he does not stand alone in his understanding of the structure and relations of the mountains of Asia, Suess makes clear in the following passage:

"The uniform structure of the Asiatic mountains has been recognized by all the most eminent authorities on this part of the world, and has been variously described according to the point of view of each observer. In Siberia, Semenow speaks of a succession of terraces; the Gobi, together with the Khingan, forms the highest step; the country of the Amur, with Sikhota-Alin, the second; the sea, with its island arcs, the third. In China, Richtnofen was impressed with the idea that the whole country sinks in great flexures to the Pacific Ocean. In Japan, Naumann compares Asia to an elevated domelike protuberance surrounded by peripheral fractures. As one stands in front of the overfolded chains of the Himalaya, says Griesbach, there seems to have been a movement of the whole mass of Asia toward the south" (III, 7).

From the Philippines to Alaska the whole front of Asia is adorned with a wonderful series of island arcs which have been likened to festoons hanging from the continental border. Concerning the origin of these, Suess says:

"Thus the east Asiatic coast does not resemble a series of independent ranges advancing toward the sea, but rather a *stupendous virgation extending over the whole breadth of Eurasia*, the successive divergence of the same folded systems which, closely crowded together in the interior of the continents, form the great and lofty highlands. In this divergence each of the great branches shows near its extremity—that is, toward the ocean—a tendency to recurve to the north, and thus arise the island festoons of east Asia" (II, 195-196).

In a general survey of the island arcs, Suess mentions the following: the arc of the Liu-kiu Islands, of South Japan, of North Japan, of central Yezo and Sakhalin, of the Kurile Islands, and a fragment of arc in central and western Kamchatka. To these must be added the most perfect arc of all, the arc of the Aleutian Islands, which Suess, however, regards as independent. All these island arcs are, of course, mountain ranges submerged beneath the ocean.

Westward from the Philippines the peripheral mountain arcs continue, and are thus enumerated by Suess:

"Five great arcs turned toward the south align themselves one after the other across the continent; these are the Malay arc, the arc of the Himalaya, the shattered outer arc of the Hindu Kush, the Iranian, and the Dinaro-Tauric arc. To these must be added still another—that which, distinguished by somewhat different characters, surrounds the western Mediterranean" (I, 505-506).

Referring to the southern part of Eurasia, which comprises the great peripheral mountain belt with which we are here most concerned, Suess says:

"A great part of this folding is of recent age, or has been continued into very recent times; it is not certain that the movement has ended" (I, 597).

And in the summary of his chapter on the relations of the Alps to the mountains of Asia, he says:

"Thus we see that since the Middle Tertiary period, and up to still more recent times, important tangential movements have taken place, and have thrown into folds a sea-bottom which extended through the middle of Europe and Asia" (I, 507).

The ranges here referred to were formed out of sediments laid down in the ancient greater Mediterranean, which Suess calls the Tethys, and of which the modern Mediterranean Sea is only a remnant.

Thus, in brief, Suess finds Eurasia to be a great unit of continental growth which has advanced to its present state by well defined steps from early, smaller beginnings in the far north. First, there was the ancient "vertex" in Siberia. This is an ancient plain, marking the planed-down surface of still more ancient rocks, which, through all the steps of continental development since pre-Cambrian times, have remained remarkably stable and free from disturbance. This plain has not been folded by any of the Paleozoic or later folding movements which have brought into being the great mountain ranges that run in concentric lines around its southeastern, southern, and southwestern sides. Through very long periods of relative quiet, sediments accumulated in the border of the sea surrounding the vertex. Then in relatively short periods of diastrophism or crustal deformation these sediments were squeezed and thrust horizontally in southerly directions—that is, toward the sea—and folded into the mountain ranges. This cycle of continental growth was repeated three times, and produced successively in three periods of folding the three principal mountain systems which characterize Eurasia. In the beginning there were several smaller separate continental elements, and they were not welded together into the one great continental unit of Eurasia until the last or Tertiary folding period. It was this last and by far the greatest of the mountain-making periods since pre-Paleozoic times that brought Eurasia to its present state.

Figure 2 shows the trend lines of the Tertiary fold-mountains of Eurasia. The older lines are omitted. The shaded parts, comprising the peninsulas of India and Arabia and part of Africa, represent the obstructive fragments of the ancient Indo-African continent against which the southward folding of the western half of Eurasia was thrust.

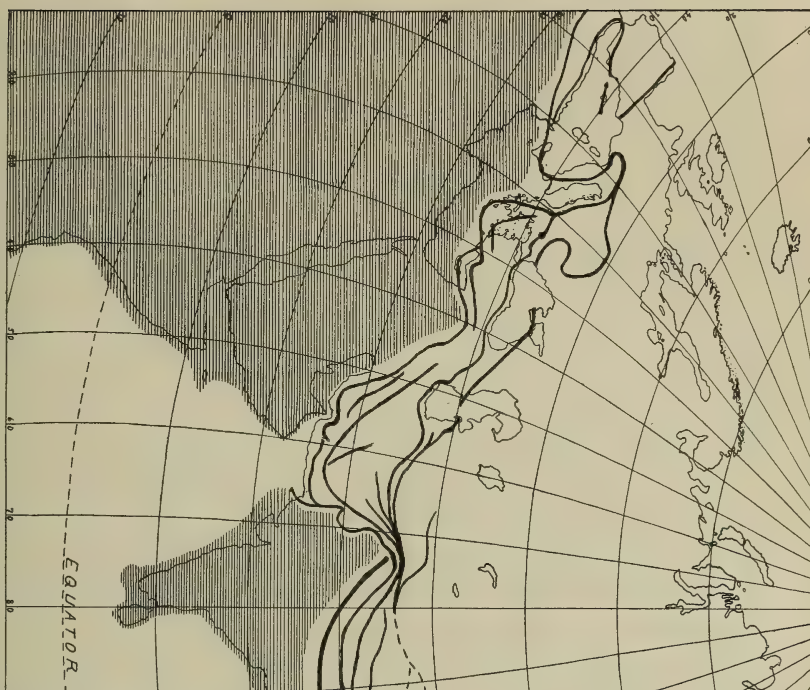

FIGURE 2.—*Eurasia*

Showing the extent and general relations of the Tertiary ranges of fold-mountains which form the peripheral system. Shows also the irregular trends of the European ranges, the Iranian and Malay earth-lobes, the Himalaya re-entrant, the island arcs of eastern Asia, the Ladrone arc, the Tuscarora and part of the Aleutian frontal deeps, and the meeting place of the Australian and Asiatic fold-lines in Borneo, Celebes, and Halmahera.

The trend-lines of the mountain ranges as shown on this map are, of course, somewhat distorted, especially in eastern Asia and in Europe, but they are much less distorted than when represented on Mercator's projection, and the proportions of the parts of Eurasia are more nearly true. The dotted areas east of Japan and south of the Aleutian arc are frontal ocean deeps.

Suess' Method of Interpretation

Suess interprets the structure of Asia chiefly by a study of the horizontal plan of its mountain ranges. These ranges mark the main structural or tectonic lines of the continent, and in the peculiar arctuate forms which characterize them, in the relation of the arc-shaped ranges to one another, in their magnitude, arrangement, and distribution with reference to the continent as a whole, and also in their relative ages and the order of their formation, Suess finds a stronger and more certain light shed upon the structure of Asia and upon the origin of that structure than in all other evidence combined. Suess has reached his grand conclusions as to the direction of crustal creep and horizontal thrust, not by the usual method of studying outcrops and cross-sections, but by a study of the trend-lines of the mountain ranges which were produced by these movements.

This method is unique, but it grew naturally and easily out of the study of the facts observed, and is not a fanciful invention of the imagination. As Suess has said, the arc-shaped ranges of Asia have deeply impressed all the students of that continent. They are the most remarkable and significant thing which the researches in that continent have revealed. While similar investigations have been carried on in all the other continents, this method of interpretation was not developed in any of them, for the evident reason that no other continent has mountain systems which reflect in their plans such simple and unequivocal expressions for the dynamic forces involved in mountain and continent making. But, having been developed in Asia, this method may possibly be applied with success to the interpretation of the other continents.

So strongly significant of crustal movement in one general direction are the lines of the mountain plan of Asia that no geologist who at the outset was free from strong hypothetical preconceptions has failed to agree with Suess in his general interpretation. Not that the other geologists join with Suess in the details of his particular hypothesis of the causes of Asiatic structure, but the general consensus of opinion among European students of Asia agrees with him in his broad conclusion that the mountain ranges were produced by tangential or horizontal thrusts acting in a general way from northerly to southerly directions.

No other method of studying the products of diastrophism or earth-deformation with the object of learning their causes gives anything like so much promise of final success as this, for none takes hold in such a broad, deep way. Suess' method is adapted to include and comprehend the broadest possible relations and aspects of the phenomena of crustal deformation. The facts dealt with by this method are not a more or less unrelated aggregation of minutiæ, as is too often the case with collections of outcrops and cross-sections; their scope and breadth are commensurate with the extent of the mountain ranges themselves or even with that of whole continents. Indeed, it is one of the objects of the present paper to endeavor to show that the method of Suess is applicable not merely to Asia and Eurasia, but to the whole northern hemisphere and to the southern hemisphere also, and hence to the whole earth; and finally, that the conclusions reached by a broad application of this method point even now very clearly to the general nature of the processes which have produced the earth's plan.

After noting the advances made by Reyer and Bertrand in the methods of study of mountain ranges in transverse section, Suess makes the following remarks on the value of his own synthetic method:

"A study of the mountain chains in transverse section is, however, only one part of our task; we must also investigate them in horizontal projection—that is, in plan. There was a time when every single anticline of the Jura was regarded as an independent axis of elevation; then it became clear that such a collection of parallel anticlines must have a common origin; next it was seen that there is a certain dependence between the Alps and the Jura; finally, the influence of the obstacle presented by the Black Forest was recognized, and it became evident that the Alps and the Jura were only parts of the southernmost, innermost, and most recent of three crescentic systems of folds which have arisen one after the other across central Europe since the close of the Silurian epoch. Thus with our increasing knowledge we are led to the conception of units of a continually ascending order, and the several anticlines of the Jura now appear to us as parts of an organic whole.

"To continue this method of synthesis, to group the folded ranges together in natural units of a still more comprehensive character, and to explain by means of a single simple expression as large a part as possible of the terrestrial folding—such is the task which now awaits the geologist. The *plan of the trend-lines*, written by nature on the face of the earth—this it is which he has to determine" (III, 3).

In the present paper Suess' method of interpretation from the trend-lines of mountain ranges is followed throughout, and is extended to the largest possible units. But his conception of the manner of deformation, by oceanic depression and tangential thrusts directed toward the oceans from certain northern vertices, or horsts, of relatively restricted area, is not adopted. In its stead an attempt is made in the closing part of this paper to determine in a general way the nature of the causes producing the tangential thrusts, particularly by a study of the largest definable units of deformation and by the groupings which the similar and dissimilar characters of these units suggest in relation to possible causes of deformation. The conclusion reached is one which Suess himself hints at in one of his later works, where he recognizes the possibility of a much broader cause than that which he discusses in the first three volumes of "The Face of the Earth."

Eurasia, the greatest Unit in the Earth's Plan

Significance of the peripheral mountain arcs of Asia

Throughout his whole discussion of the mountain systems of Asia, Suess dwells continually on the significance of the mountain arcs, and especially on those of the peripheral belt. He notes that they all bend to the southward—to the southeast from eastern Asia, to the south from southern Asia, and to the southwest and south from southwestern Asia; that they are overthrust against the northern side of the obstructing tableland of Indo-Africa, and show peculiar forms which arise from adaptation to the form of the obstructing mass; that the island arcs along the east coast, where no obstruction was met, bend out even more perfectly toward the deep depression of the Pacific; that the southward bending of the arcs indicates a connection between the different parts of all this vast region and must have arisen from a common cause, and finally that these characters all contribute to the conclusion that the entire peripheral mountain system of Asia was folded toward the south by horizontal thrust forces acting in that direction. It seems impossible to contemplate a plan of the trend-lines of the peripheral ranges, such as is shown in figure 2, without reaching these conclusions.

The trend-lines show, with two or three exceptions, simple arc-forms bending to the south along the entire front from Asia Minor to Alaska. Their simplicity of form and their relations to one another are such as seem to be attributable only to a single thrusting force acting throughout the whole process of folding substantially in one direction, for there appears to be no evidence of complexity resulting from thrusts in different directions, such as is found in Europe. The arc of the main range of the Himalaya is about 1,500 miles long and is a curve of wonderful simplicity and perfection. It is an almost perfect arc of a circle with a radius of nearly 1,300 miles, and its curvature is remarkably perfect for a feature of this kind. The island arcs off the east coast are almost as nearly circular in their curvature. But westward from Burma the first range, omitting the Himalaya arc, shows many irregularities that break up the simplicity of its curves.

From Asia Minor to the Philippines the peripheral belt of Tertiary folds is not a single folded line, but consists of two or three lines, sometimes more, lying one behind the other. From the Philippines to Alaska, however, the Tertiary belt is a single fold-line, so far as known. The reason for this difference is not known with certainty. As Suess says, we do not know the character of the platforms upon which lie the seas behind the island arcs; there may be other weaker, lower fold-lines behind the arcs, or the platforms may be composed of ancient, crystalline rocks which moved as "plates" without parallel foldings. In Europe and western Asia the resistance of the Indo-African plateau may have contributed largely to the making of parellel fold-lines, but this would hardly apply to the Malay arc between Burma and the Philippines. Nevertheless, the absence of any obstruction along the east coast would seem to have favored simpler results there.

The peripheral mountain arcs form a continuous frontal fold for the whole southern border of the continent, and are apparently all of one age. Regarded as a product of crustal deformation, this fold appears to be a unit in both extent and time, and it is therefore a unit in dynamic process also. A mighty creeping movement of the earth's crust from the north toward every part of the vast periphery appears to have taken place, and the area of earth-crust involved appears to have been as great or greater than the entire expanse of Asia. This idea is very different from the conception of Suess, who pictures the ancient vertex in Siberia as the center from which all the movements took place, the vertex remaining unmoved, while the crust around it moved away in slightly divergent southerly directions.

THE HIMALAYA RE-ENTRANT AND THE MALAY EARTH-LOBE

The most pronounced departure, however, from a fairly even front for Asia is found in the contrasted forms of the Himalaya re-entrant and the Malay earth-lobe. If we contemplate the plan of the trend-lines, as shown in figure 2 for these two features, it seems apparent that it was the obstructing action of the Indian peninsula which produced the great Himalaya re-entrant. It was the tremendous resistance offered by this fragment of the ancient Gondwana-land which held back the advancing folds to the line of the Himalaya. The effect seen in horizontal plan is as though India had held back an advancing curtain in a very pronounced way, as indeed it did, for the curtain was the crustal sheet of Asia.

The occurrence of such an obstruction in the way of the southward moving crustal sheet must necessarily have produced some very characteristic effects, and some of these effects could be anticipated with much confidence by the application of well-known principles. It would be expected, for example, that the folds would be most closely pressed together at the most northerly point of the resisting obstacle, where the obstructing effect would be greatest, and that the folds would bend or lap around on either side of the obstructing mass so as to inclose it within a re-entrant angle of the general front. It would be expected also that the vertical component of movement expressed by positive elevation of mountain ranges and plateaus would be greatest against that same point.

All these effects are conspicuously present in the Himalaya re-entrant. The Pamir plateau, the highest on the earth, is close north of the extreme northern point of India, and it is here that the great Hindu-Kush, Kuen-Luen, Altai, and other ranges converge in the Pamir plateau, with the northwest end of the Himalaya range abutting against its southern side. The Himalaya is the most majestic mountain range on the earth and some of its peaks are the highest. Who can doubt that the great height of Gaurisanker and the Pamir are due chiefly to the intensified elevation caused by the obstructing action of the Indian peninsula?

A large area of Asia north of the Himalaya is a high plateau with lofty mountain ranges. At the east the Himalaya range ends abruptly on the Brahmaputra at the great bend, and several lesser mountain ranges wrap themselves around the east end of the Himalaya, some of them changing their trend from due east and west, north of the Himalaya, to northeast and southwest south of the great bend. The simplicity of the relations of all these features is such that the obstructing action of India to the southward advance of the crustal sheet seems the only possible explanation.

From the eastern end of the Himalaya the trend of the peripheral range runs far to the south, curving gradually to the east, and returning northward through the Philippines to Formosa. This great excursion of the peripheral ranges to a point seven hundred miles south of the equator incloses an immense area, including the South China Sea, the Java, Celebes and Sulu seas, the Gulf of Pegu, the islands of Sumatra, Java, Borneo, Celebes, and Philippines, the Malay Peninsula, Burma, Siam, Annam, and part of southern China. This immense area is far too great to be classed as a mere arc along with the other mountain arcs; it is in truth a great earth-lobe, analogous to some of the great ice-lobes of the Pleistocene ice-sheet of North America. Suess himself suggests this comparison in one of his later works, where he says:

"One can also recognize a certain resemblance between these curved chains [of Asia] and the course of the moraines, and also the forms of the glacier lobes which Chamberlin draws across the east of the United States."[3]

Its periphery is made up of six or seven lesser mountain arcs joined end to end in a curving course, so as to define the boundaries of the lobe. On its base between the eastern end of the Himalaya and the Island of Formosa this lobe is about 1,700 miles across, and from base to outer extremity it measures about 2,500 miles. It is interesting to note that the Malay earth-lobe presents certain well marked antitheses to the Himalaya re-entrant, and that they are all dynamically normal. Corresponding to a region of relatively free and partly dispersive crustal movements, without obstructing masses, the peripheral ranges of the Malay lobe have comparatively low altitudes, and further, corresponding to an axis of more extensive and perhaps more rapid crustal movement, some of these ranges show unusual volcanic activity. The Java arc in particular is a veritable fire line, and its relatively low mountain basement is almost entirely covered up by volcanic products. Here, then, was the relatively free spreading of a great earth-lobe, the thrust forces dying out in dispersive movements, while in the more severely compressed and overheightened Himalaya and the Pamir we see the effects of crustal movement retarded by a great and effectively resistant obstruction.

There seems to be little doubt that the projection of this remarkable earth-lobe so far to the south on a path lying next east of the Himalaya is in some degree a compensation for the obstructing effect of India. The advance of the crustal sheet in the region north of Indian was so strongly retarded by the Indian mass that the force of the movement against the Himalaya was partly deflected eastward into the Malay lobe. In this way the thrust forces running south along the axis of the Malay lobe were intensified and accelerated, just as a stream of water, meeting an obstruction which fills half the width of its channel, is retarded and slightly raised against the obstruction, only to rush with accelerated velocity through the remaining constricted space. If there had been no obstructing Indian peninsula, it seems likely that these two areas would have been equalized, and that the front line of Asia would have run in a broad curve sweeping from the east end of Arabia to Formosa, without, in all probability, reaching farther south than the tenth degree of north

[3] Bulletin of the Geological Society of America, vol. 11, p. 105.

latitude. In the following passage Suess describes an interesting relation between the Himalaya and Malay arcs:

"We shall show later, with greater detail than we have yet done, that the Himalaya actually terminates on the Brahmaputra. There are chains lying behind the Himalaya joining the meridional chains of Yunnan which pass the end of the Himalaya and are continued in the Malay arc. This arc we have traced through the Banda Islands as far as the coast of New Guinea. But although to the south it passes considerably beyond the equator, yet in a tectonic sense it lies wholly behind the Himalaya, or if we were to number the great folded ranges from the exterior inwards, the Himalaya would receive the number 1 and the Malay arc the number 2" (II, 195).

In the region of Borneo, Celebes, and eastward there are some singular complexities of the trend-lines. These, however, do not belong to Asia alone and will be considered under a separate head.

On the map (figure 2) a broken line is drawn from the west end of New Guinea toward the northeast to the Ladrone Islands, and thence northward to the great fossa in Hondo, Japan. This line appears to mark a submerged mountain range, as shown on bathymetric maps, and probably represents a broadening or uncompleted enlargement of the Malay lobe. This, however, is a matter for further investigation.

Along the south or east front of some of the interior mountain ranges of Asia, Suess, Richthofen, and others have described what they call disjunctive lines or faults with great downthrow to the east, south, or southeast. Along these lines great platforms broke from the high central plateau and settled toward the Pacific. It may be that this movement was secondary or reactionary, and was caused by a too great elevation of the lands of central Asia at the most active stage of folding.

On the west side of India the crustal sheet pressed southward into the gap between the resistant masses of India and Arabia, and formed another distinct feature which we may call the Iranian earth-lobe. It is much smaller than the Malay lobe, but is, nevertheless, distinctly accentuated by the obstructing action of India. The front range of this lobe has two small, sharp re-entrants which appear to correspond to saliences of the obstructing mass. One is on the east side and incloses the plain of Katschi in northeastern Beluchistan; the other is toward the west side, and is marked by the northward bending of the Strait of Ormuz. The Ahkdar Mountain range attains an altitude of more than 6,000 feet back of Muscat, on the east coast of Arabia. This range runs northward into the Strait of Ormuz with decreasing altitude, as though pitching downward to the north under the Iranian earth-lobe. As the Persian Gulf and the Tigris-Euphrates Valley appear to be a sunken fore-land, so the Strait of Ormuz appears to be a passage over a depressed mountain range.

West of the lower course of the Indus the Kirthar range runs directly south, and then curves southwestward toward the sea at Cape Monze. It appears to continue some distance to the southwest beneath the sea, for the soundings show a deep trough extending back to the northeast along the north side of the submarine line of the range. The position of this range suggests a folded arc curving toward the west through the northern part of the Arabian Sea, but remaining undeveloped. Its trend suggests a continuation in the Ahkdar range of Arabia, which curves back toward the north on the west side, but present knowledge indicates the latter range to be older and to belong to the ancient Indo-African tableland. These features invite further investigation.

THE PERIPHERAL RANGES IN EUROPE

The trend-lines of the Tertiary mountain ranges of Europe are much more complicated than those of Asia. They show a tendency to a dominance of east and west trends, although the Apennine and Dinaric ranges, with northwest-to-southeast trends, form a marked exception, and a considerable part of the Carpathian fold takes the same course. The most remarkable forms, however, are the sharply bent arcs of short radius, the Roumanian arc, the arc of the western Alps, and the arc of the Betic cordillera at the western end of the Mediterranean. All of these present sharply convex fronts toward the west.

In discussing the trend-lines of the European ranges, however, Suess departs somewhat from the methods and principles which he has used so successfully in Asia, and his language in some passages seems to contradict that of others. In Asia, Suess found the direction of overthrusts in the peripheral belt to be invariably toward the south, thus agreeing well with his conclusions on the direction of tangential thrust from the southward convexities of the arcs, and the evident southward compression against India. But one can not be sure upon which kind of evidence he relies the more, overthrusts or direction of arc bending. On the whole, one is inclined to believe that he relies more upon the latter; yet, when he passes over to Europe and discusses the ranges there, he finds a confusion of trend-lines among which, although east-and-west lines are dominant, others are prominent, the Carpathians and the Alps especially showing northward convexities. The three arcs sharply convex to the west Suess attributes to a tangential thrust from the east. The arcs of the Carpathians and the Alps are convex to the north, and from his point of view indicate tangential thrusts in that direction. The arc of the Apennines is slightly convex to the northeast, while the great curve made by the Apennines and the Atlas of northern Africa is convex to the southeast. The southern range of the Atlas is nearly a straight line, and the Pyrenees, like the Caucasus, are substantially rectilinear.

But, in addition to the northward bending which Suess finds in the Carpathians and the Alps, he finds also that both of these ranges are strongly overthrust toward the north, and that the older ranges also show great overthrusts toward the north or northwest, as in Belgium, Scotland, etcetera. In Scandinavia, however, the greatest of all the overthrusts is toward the east-southeast. On these evidences Suess concludes that the thrust forces in Europe acted mainly toward the north, or contrary to their direction in Asia, and, what is much more important, his language seems to convey the idea that the whole crustal movement in Europe was toward the north. This conclusion he seems to rest on the few cases of northward convexities with associated northward overthrusts.

In some of his broad, generalized statements Suess' words seem to imply clearly enough a general southward tangential movement in Europe the same as in Asia, as, where he says: "*The whole southern border of Eurasia advances in a series of great folds toward Indo-Africa*" (I, 596). Again, in enumerating the continental units he mentions first, "*Indo-Africa,* the greatest tableland of the earth, limited on its northern border, from the point where the Wady Draa discharges into the Atlantic Ocean to the mouth of the Brahmaputra, by the folds of Eurasia advancing to the south" (I, 600). But in discussing the relation of the Alps to the mountains of Asia he says:

"We observe as a remarkable phenomenon that from the Caucasus onwards [westward] the tangential movement is not, as in the Asiatic chains, directed to the south, but to the north, and that on the northern border of the Carpathians all the indications appear of an extensive overthrusting on to two forelands of completely different structure, the Russian Platform and the Sudetes" (I, 500).

In the next paragraph he observes that "it would seem as if in Asia tangential movement or lateral compression had occurred almost exclusively in the direction of the meridians of longitude, but that here [in Europe] it had taken place also in the direction of the parallels of latitude, and it is precisely in this region that the Carpathians are driven out toward the north in so striking a fashion."

In these last two passages, and in others that might be quoted, Suess seems to abandon in part his broader method of interpretation for the older method, which depends mainly upon the study of local structural details, and in doing this he seems to lose sight of a very important distinction which ought to be kept constantly in view. Overthrusts and local convexities of trend-lines may not accord with the direction of general crustal creep in the same region, and surely it is of the first importance to determine correctly the larger of these facts—the direction of the general crustal creep. This can be done safely only by the broadest possible methods, such as have been used for Asia. Indeed, it is by an extension of the reasoning for Asia to the European field that this question can be most clearly and safely determined.

In Asia the proof that the crustal sheet moved southward as a unit does not rest alone on the existence and relations of the single frontal fold-line, but upon the whole belt of subparallel Tertiary ranges, extending from the Philippines to Asia Minor. The belt as a whole is peripheral in its nature; it is the crumpled margin of the crustal sheet. The belt continues into Europe with about the same width and in the same general relations—as a peripheral belt along the southern margin of the continental sheet.

Suess remarks that there is no natural line of demarkation between Asia and Europe, and Penck happily describes Europe as "peninsular Eurasia."[4] Suess points out the fact that the fold of the Caucasus appears to continue into Europe in the Roumanian arc, the Carpathians, and the Alps, while the Taurus fold continues in the Dinaric range of Europe. In short, the Tertiary fold-belt extends right through from Asia into Europe without any change, except that its simplicity in Asia is replaced by complexity in Europe. The general relations are absolutely identical.

Broad facts like these are of a much higher order of value in determining the direction of general crustal creep than are facts relating to overthrusts and occasional exceptionally directed convexities of trend. The peculiarities and exceptional features in Europe may be explained by other causes, and can not be safely set up as proof of the direction of general crustal movement.

There are at least three causes for irregularity among the trend-lines of the European ranges. The first and most important is the relative smallness of the European crustal sheet, with consequent feebleness of the thrust forces; second, the obstructing and complicating action of block-like masses of the older European ranges, where included within the belt of the Tertiary folds; and, third, the tangential thrust from the east, producing the Roumanian, Alpine, and Betic arcs, as described by Suess.

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[4] Science, February 26, 1909, p. 322.

The crustal sheet or "plate," as Suess calls it, lying north and northwest of the European Tertiary ranges, was quite small as compared with that which lay to the north of the Himalaya and the Malay and Iranian earth-lobes, and it was the magnitude or mass of this "plate" which in each case determined the power of the crustal advance and probably also the horizontal distance of the advance. In Asia the Tertiary advance closed and completely overwhelmed the ancient greater Mediterranean Sea, the Tethys of Suess, whereas in Europe the same movement fell far short of this result and closed only a part of the sea, leaving the modern Mediterranean in its present state. It can not be doubted that the southward pressure of the creeping crust was far greater in Asia than in Europe. Where the forward movement of the crust was more vigorous, as in Asia, minor causes tending to interfere and produce irregularities were overwhelmed; but in Europe, where the movement was relatively feeble, the minor forces were favored and the impress of their action remains today.

The thrust from the east, seen in the Roumanian, Alpine, and Betic arcs, appears to have been a deflected force arising probably from the resistance of Indo-Africa to the southward crustal movement in Asia. Although it produced locally a marked effect, it was apparently a relatively feeble force.

On general principles one is inclined to believe that forward overthrusts—that is, moving in the same direction as the general crustal creep, like that at the base of the Himalaya—are likely to be of greater extent than underthrusts which only produce the effect of overthrusts in a backward or opposite direction. Agreeably with this idea, the great overthrust to the east-southeast in Scandinavia has a length of nine degrees in latitude and a known width of over 100 kilometers. This is much more extensive than any of the others in Europe, and the others are all in the opposite direction. It seems probable, therefore, that the Scandinavian case is a true forward overthrust, while the others in Europe are southward or southeastward underthrusts. This, of course, does not take away the appearance of overthrusting in these latter cases, but the tangential force which affected the mass above the thrust plane is in such cases to be regarded as a reflex thrust force, directed backward over the advancing undermass. The upper mass in a case of underthrust might be described as a backward overthrust in distinction from a forward or true overthrust.

The resistance of the African plateau may also have contributed something to the irregular forms in Europe, especially in favoring the persistence of some of the Mediterranean basins, or possibly the making of them. The Atlas Mountain ranges of Africa belong structurally to the

Tertiary folded system of Europe and to the peripheral system of Eurasia.

Since there is no ground for separating Europe from Asia as dynamic units in the Tertiary deformation, they should be taken together as one unit, and the Tertiary ranges of the entire peripheral belt should be regarded as the product of southward creep of the entire crustal sheet of Eurasia. But there is still a little more to be added even to this great unit.

THE ARC OF THE ALEUTIAN ISLANDS

Suess regards the arc of the Aleutian Islands as an independent line, not to be counted with the island arcs of eastern Asia, and he counts it as a distinct and separate element in enumerating the boundaries of the Pacific. This is only partly justified, for this arc is, in fact, distinctly Asiatic in all its characteristics and affinities. The Asiatic character of this arc is strongly shown in its pronounced curvature and its grand sweep. It is, indeed, the most perfect of all the island arcs, and, like the arcs of the Kuriles and north Japan, has a long, narrow ocean deep close in front of it. Its backland belongs about two-thirds to Asia and one-third to North America. The mountain chain which forms the arc rises from the sea as it approaches Alaska, and continues in the same curve to the highest part of the Alaskan Mountains.

While the Aleutian arc is a perfect type of the Asiatic arcs, no such arc occurs in either of the American continents. Probably Suess regarded it as independent, because it is so situated that it could not be related to his Siberian vertex in the way that he finds the other island arcs to be; but this is not believed to be an essential distinction. That part of Asia which forms the backland of the western part of this arc is just as much a part of the great crustal sheet of Eurasia as any other part, and the distinctly Asiatic type of the arc shows that whatever special conditions determined the peculiarities of the other island arcs affected the backland of the Aleutian arc in the same way.

When the Asiatic character of the Aleutian arc is recognized it becomes at once apparent that the crustal sheet of Eurasia is not limited on the east by a line through Bering Strait dividing this arc and its backland, but includes the whole arc and the whole of its backland. Thus, Asiatic character is carried eastward to the heart of the Alaskan Mountains, where the curve of the Aleutian arc meets the Cordilleran ranges of North America in a sharp angle. This meeting point falls near the 148th meridian of west longitude, and when we consider continental boundaries with reference to Tertiary diastrophism, we must include in the crustal sheet of Eurasia all that part of Alaska which lies west of this meridian.

Thus Eurasia, considered as a crustal unit in the Tertiary movements, includes all of Europe with the Atlas ranges and Canary Islands of northwestern Africa; all of Asia excepting the peninsulas of Arabia and India, and in addition all that part of North America which lies west of the mountain angle of Alaska. It seems certain that all this vast crustal sheet was affected by a horizontal creeping movement in the Tertiary age, that it all moved in a southerly direction substantially as a unit, and that the entire belt of Tertiary fold-mountains which forms its southern periphery was made at that time and by that movement.

FRONTAL OCEANIC DEEPS

The deepest parts of the ocean are found mostly in long, narrow troughs closely parallel to the continental borders, especially that of eastern Asia.[5] The position and relation of these deeps are truly remarkable. The Tuscarora deep, with a depth of more than 5 miles, is the deepest abyss now known. It lies in front of the Kurile Island arc and the arc of north Japan (see figure 2). An even more remarkable deep is that which lies close along the entire front of the great curved arc of the Aleutian Islands and includes the Supan and Maury deeps. This trough is partly shown in figure 2. The principal frontal deeps are shown in figure 7.

Other deeps in the same relation, but smaller, occur along the east side of a submerged escarpment running north from New Zealand. These lie in the northwest part of the more extensive Aldrich deep. There are deeps along the west coast of South America, such as the Bartholomew, Richards, and others. Deeps with circular or irregular outlines occur in other relations not so clearly dependent upon adjacent land-masses. Such are the deeps of the Atlantic and the line of deeps running north from the Aldrich deep through the middle of the Pacific. The Challenger deep is near the junction of the Ladrone and western Caroline Island chains, while the Wharton deep lies partly between Australia and the Malay arc. Deep holes, like the Bartlett and Weber deeps, are characteristic of all the Mediterranean seas.

The Tuscarora deep and that in front of the Aleutian arc seem clearly linked causally with the continental border and the great mountain ranges

[5] See Sir John Murray's "Bathymetrical chart of the oceans." Scottish Geographic Magazine, vol. xv, no. 10, October, 1899; opposite p. 560. Reproduced in Chamberlin and Salisbury's Geology, vol. i, p. 10. The portion covering the Atlantic Ocean is reproduced as plate 4, facing page 217.

which stand adjacent to them. They are of the nature of sunken or depressed forelands, and are apparently due to the stupendous weight and pressure of the adjacent ranges. These arcs are no doubt more or less overthrust upon the ocean floor, and the troughs are probably due in part to elastic yielding and perhaps in part also to plastic flow.

The most strongly marked deeps are close in front of island arcs which represent submerged mountain ranges. Evidently the reason that the Tuscarora and Aleutian deeps remain unfilled today is that the ranges to which they are related have remained submerged, have suffered little or no erosion, and hence have supplied very little sediment. Other similar frontal depressions situated close to continental lands which supplied great quantities of sediment have been partly or wholly filled. Such are the valleys of the Ganges and Indus in India, the Tigris-Euphrates Valley and the Persian Gulf, and also the Adriatic Sea and the Po Valley. Such troughs, growing deeper while sediments are being deposited in them, furnish a possible explanation of certain sedimentary strata whose great thickness and shallow-water character seem to demand subsidence during deposition.

The fact that the greatest deeps, both unfilled and filled, lie close to the front of the peripheral ranges of Eurasia, the greatest of the continental units, adds one more significant group of facts to the great aggregate, showing how much more vigorous were the Tertiary crustal movements there than in any other part of the world; and they join with the other evidences mentioned above, which show a general southward crustal movement for the whole of Eurasia.

The Relation of North America to Eurasia

THE MOUNTAIN KNOT OF ALASKA

In his earlier writings, Suess regards North America as a continental unit which moved in harmony with the Tertiary movement of eastern Asia—that is, it was folded toward the Pacific Ocean. Referring to North America, Suess says: "So far as folding is known in this continent, it appears to be everywhere directed to the west" (I, 600).

It may be observed here, however, that the Tertiary folds bordering the Pacific are mainly folded toward the *southwest*, rather than to the west, as Suess states, and that only in the States of Oregon and Washington are they folded to the west.

On the same page Suess observes further that—

"After having described the manner in which the syntactic arcs of the great chains push forward against the north of the Indian Peninsula, we observe that a similar advance of syntactic arcs takes place toward the north of the Pacific Ocean, and that a special tectonic homology exists between that fragment of ancient table-land and this part of the ocean."

From these passages it seems clear that Suess regarded the Cordilleran ranges of British Columbia as pressing toward the southwest to meet the eastern end of the Aleutian arc pressing toward the southeast, and this is apparently the true relation. There was thus a convergence of crustal movements in the mountain knot of Alaska, and it was the conflict of these movements which intensified the mountain making at the angle and gave the mountain knot its greater breadth and height. Figure 3 shows the mountain knot, with part of the Aleutian range which enters it from the southwest and part of the Cordilleran range which enters it from the southeast. The shaded part is 5,000 to 10,000 feet in altitude and the black parts 10,000 feet or more.

The morainic accumulations of the Pleistocene ice-sheet in North America present homologous forms that are very instructive. These are the interlobate moraines which were produced in re-entrant angles of the ice-front, where the fronts of two adjacent great lobes of the ice-sheet came together on converging lines. The mountain knot of Alaska is in a precisely similar sense an interlobate form—a confusion and intensifying of mountain making in the angle between two great earth-lobes, or two crustal sheets moving on converging lines. Just as interlobate moraines are higher, more bulky, and more tumultuous in form than either of the single morainic ridges approaching the interlobate angle, so the mountain knot of Alaska is broader and higher than either of the ranges approaching it. If the Cordilleran ranges of British Columbia had been folded toward the northeast—that is, away from the ocean—there would be no reason for the existence of the mountain knot; and still less if we suppose, further, that the eastern part of the Aleutian range had been folded to the northwest. There would then be diverging movements from the place of the mountain knot—a condition hardly favorable for the formation of such a feature.

American geologists, following H. D. Rogers, Dana, Leconte, Dutton, and others in their interpretation of Appalachian structure, made many years ago, derive the thrusts producing the folding of that range from the direction of the Atlantic Ocean. No doubt this is correct so far as relates to the immediate thrust forces involved—that is, to those which affected the upper or outer parts of the crustal sheet and produced the Appalachian folds. But these authors make no distinction between the relatively superficial thrust movements and the deeper general creeping movement which involved the whole crustal sheet of the continent, as it was then, and reached downward to or into the zone of rock flowage. The variously directed thrusts which affect the more superficial parts may, according to local conditions, act in any horizontal direction, but usually either in the same direction as the general crustal movement or in the opposite direction. The same idea was later applied to the Rocky Mountains and to the Cordilleran ranges bordering the Pacific, and the thrust forces there were derived from the Pacific depression.

FIGURE 3.—*Alaska*

Showing the mountain knot, part of the Aleutian Island arc, and part of the Cordilleran ranges of British Columbia and Alaska. The arrows show the supposed direction of crustal movements.

It seems certain, however, that the relation of the Cordilleran to the Aleutian range in the mountain knot of Alaska shows that the general crustal movement of North America in the Tertiary age was toward the Pacific, and hence that the great eastward and northeastward overthrusts of the Rocky Mountain region are in reality underthrusts, or reflex overthrusts, directed backward over the southwestward general crustal movement. At these localities the southwestward underthrust of the deeper parts was the primary movement, and the apparent northeastward overthrust observed in the superficial parts is regarded as secondary and reflex in its nature.

As shown in the two quotations given above from Suess, this was in substance his original interpretation of the part played by North America in the Tertiary mountain making which set the present boundaries to the Pacific. He regarded the crustal sheet of North America as folded southwestward toward the Pacific. Thus, on principles derived from his study of Asia, Suess generalized from Eurasia to North America, and concluded that the latter, like the former, had been folded toward the great ocean.

When Suess arrived at this generalization he had accomplished a great and magnificent result for geology, for he showed that North America, like Eurasia, had been affected in Tertiary times by a crustal movement in a southerly direction—not exactly to the south, but southward with a strong deflection to the west, though not more strongly than was the southward movement in eastern Asia deflected toward the east. In this conclusion Suess had completed in rough outline the Tertiary tectonic history of the northern hemisphere. He had put both of the great northern continents into the same category with reference to Tertiary crustal movements. Regarding each northern continent as a crustal unit, Suess found that Indo-Africa had remained stationary, or at least without tangential movements, but that both Eurasia and North America had been affected by tangential movements in the same general direction—that is, toward the south. It should be noted that in this distribution there is a certain relation to latitude, for Indo-Africa, lying mainly in the tropical regions, remained unmoved, while Eurasia and North America, each extending vast areas far to the north, both of them into the arctic regions, crept away to the south.

Here, then, is a fact as broad as the northern hemisphere. Both of the only two continents whose crustal sheets reached far to the north moved in the Tertiary age from north to south. Such a fact as this may be taken as the concrete expression of a general law of wider scope. Thus, if the forces of Tertiary diastrophism caused the earth's crust to move from north to south in the northern hemisphere, may we not take this distribution of the deforming force to be characteristic and fundamental? Putting it in abstract form, may we not say that the deforming force caused crustal creep from high latitudes toward low latitudes? But if this statement expresses the truth it ought to be as applicable to the southern hemisphere as to the northern, and here we are naturally inclined to turn to the antipodes to see what the evidence is there.

However, before turning to this new field there remains one other important body of facts which bears strongly upon the direction and amount of movement of the North American crustal sheet.

GREENLAND, THE GREAT NORTHERN HORST

If further evidence were needed to make sure that in the Tertiary diastrophism North America moved toward the southwest—toward the Pacific and the Tertiary fold mountains along its border—it may be found in the remarkable relation of Greenland to North America.

Suess remarks that "Greenland is a horst of the first order between two or more sunken areas of different age" (II, 294). But Suess' conclusion was based mainly on different evidence from that offered here.

A map of Greenland and its environs on a large scale shows some remarkable characteristics in the outlines of the channels, straits, and bays on its northern and western sides. These are shown fairly well in figure 4.

Amid such a tangle of irregular straits and channels as separate the islands of the archipelago west of Greenland, it is quite surprising to find a passage so straight and persistent as that which separates Grant Land, Grinnell Land, and Ellesmere Land from the north part of Greenland. It seems like a distinct rift-line, and the question arises as to the direction and amount of movement along it. It is quite different in character from the great rifts or fault lines which Suess supposes to form the sharply cut boundaries of the east and west sides of India, Africa, Madagascar, and Greenland. It is a relatively narrow passage, and one seems driven to the conclusion that the displacement along it was a horizontal movement parallel with the rift. In looking for the direction, it seems impossible to suppose Greenland to have moved toward North America and the land on the west side of the rift relatively in the opposite direction, for in that case the movement would only have made Baffin Bay, Davis Strait, and the Labrador Sea more narrow, and there would be no reason to expect any element of parallelism in their sides. Besides, if Greenland was formerly farther east the straight coast along the north side of Peary Land would not necessarily be related to or determined by the course of the rift; it might be so related or it might not. Further, there is no independent evidence that Greenland has moved at all, but in the mountain knot of Alaska we have independent evidence that North America has moved toward the southwest. Thus we may conclude, at least provisionally, that it was North America that moved away from Greenland, not *vice versa*.

If, then, by reversing the process, North America be in imagination pressed back northeastward to a complete union with Greenland, it is evident that the Labrador Sea, Davis Strait, and Baffin Bay would be

FIGURE 4.—*Greenland and the Arctic Archipelago*

Showing the rift valleys on the northwestern and western sides of Greenland. The arrows show the supposed direction of crustal creep and the lines AA, BB, etcetera, show the supposed distance of movement.

closed and obliterated entirely, and that Grant Land, Grinnell Land, and Ellesmere Land would be thrust northeastward past the north end of Greenland along the line of the rift—that is, along the line of Smith Sound and Kennedy and Robeson channels produced.

It is surprising what relations a few measurements reveal in this region. Suppose Grant Land to have been situated formerly close north of Peary Land, from which it was then separated only by the rift valley. Its position in this relation is sketched in a broken line in figure 4, and shows the east coast of the two regions to form a nearly north-and-south line. If a straight line AA be drawn along the axis of the rift from a point close off the extreme eastern end of Grant Land to another point similarly related to the extreme eastern end of Grand Land *in its assumed former position,* the length of that line is about 330 miles. It is noticeable that the rift valley curves slightly to the south as it runs along the northwest coast of Greenland, and perhaps eastern Grant Land should have been placed a little closer to Peary Land. But if the lines BB, CC, DD, EE, FF, and GG be drawn nearly parallel to AA, it will be found that some of them, especially DD and FF, connecting the opposite shores of Baffin Bay, are of the same length as AA, and that EE and GG are suggestively near the same length. It is certainly significant that the distance across Baffin Bay on lines parallel to AA are so nearly of the same length. Baffin Land, therefore, appears to have been pulled away from Greenland in the same direction as Grant Land, and, what is more significant, it appears to have moved the same distance. If this be true, then we may believe that the bays or inlets marked on opposite sides of the rift valley at the ends of the lines BB and CC were offset by the movement and were formerly exact opposites. Too much importance ought not to be attached to these two lines now, but it is not impossible that the correspondence of these features may some day be proved by geological investigations.

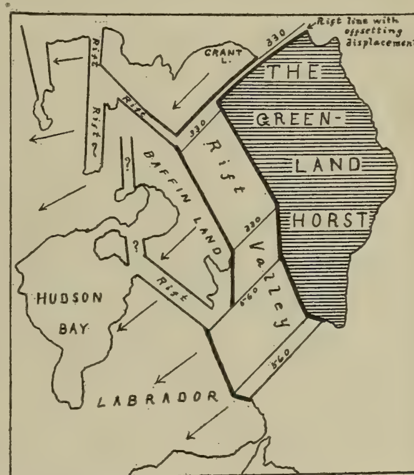

FIGURE 5.—*Diagram of Greenland Rifts*

Shows offsetting rift on northwest side of Greenland, open rifts of two widths on the west side, and several smaller subsidiary rifts farther west. The arrows show the direction of crustal movement, Greenland remaining stationary.

Up to this point some doubt might be entertained as to the supposed value of these relations and measurements. But one further fact of a strongly corroborative character remains to be mentioned. Although Grant Land and Baffin Land moved over 300 miles to the southwest, they did not move as far as did Labrador and the main body of the continent. The relation of the coast of Labrador to the west coast of the south part of Greenland is truly remarkable. This is shown by the lines LL, MM, NN, and OO. These lines are parallel with the lines DD and FF on Baffin Bay, but they are considerably longer, being each about 560 miles. Thus for a distance of about 450 miles the two shores of the Labrador Sea, although now 560 miles apart in the direction of the rift along the northwest side of Greenland, are almost exactly parallel and the geological age and structure of the rocks, so far as known, are the same. If the crust pulled away evenly, as these facts suggest, one would expect Grant Land and Baffin Land to be separated from the main body of the continent by other narrower rifts. Such rifts may be represented by the long, straight channel of Lancaster Sound, Barrow Strait, Melville Sound, and Banks Strait. A longer, less continuous passage, probably representing a wider rift, follows Hudson Strait, Fox Channel, Gulf of Boothia, and McClintock Channel.

We seem to have here a great irregular rift line along which North America has been torn away from Greenland. One part, extending along the northwest coast of Greenland, is a longitudinal rift, a great fault line with horizontal offsetting displacement. The other part, comprising Baffin Bay, Davis Strait, and the Labrador Sea, is a transverse rift along which one side was pulled horizontally away from the other. The two together are over 2,500 miles long. Then there are also the lesser transverse rifts mentioned above.

Perhaps no one of these measurements or relations taken by itself is of much value, but the assembled group makes a strong case for the pulling away of North America from Greenland. The Labrador coast is high and bold, and the Greenland coast facing it is moderately so. Both coasts have deep water close off shore. The parting of these shores can hardly be more recent than the Tertiary, nor is it easy to believe that it is much older. Even if it was so recent as the Tertiary, it is quite surprising to find the opposite walls of a rift 450 miles long pulled 560 miles apart, and still remaining so strikingly parallel; and this, in spite of all the elements of irregularity which might be expected in such a movement, in spite of the largely accidental relation of the sea surface to the rift walls, and in spite of all the erosion that has taken place since. It seems altogether incredible that such characters should have been preserved from times much older than the Tertiary. Labrador is solidly intact with the main body of the continent, and the rift of the Labrador Sea may therefore be taken tentatively as an approximate measure of the distance of the horizontal crustal movement of North Amrica in the Tertiary diastrophism.

M. L. de Launay, probably following the suggestion of Suess, placed a Tertiary rift along the axis of Baffin Bay, Davis Strait, and the Labrador Sea, and also one on the east side of Greenland and southward through the Atlantic, but he does not appear to have noticed the longitudinal rift on the northwest side and the very significant measurements on the lines parallel with it.[6]

On the remaining sides of Greenland there are no suggestive parallel coasts. But it seems certain that the crustal sheet of Eurasia pulled

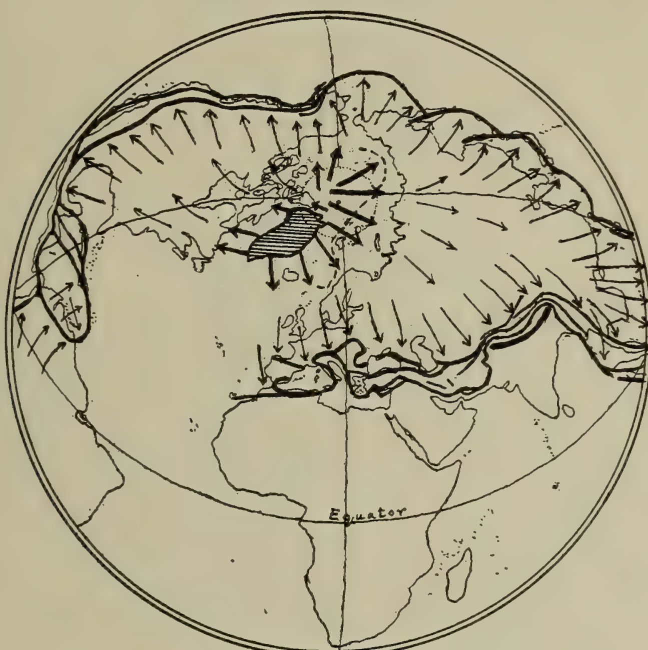

FIGURE 6.—*The Landsphere*

Showing the relation of Greenland to the surrounding continents and to the peripheral mountain ranges of Eurasia and North America. The light arrows show the direction of crustal creep and dispersion. The heavy arrows radiating from Greenland and the pole show roughly by their lengths the relative distances the continents have moved toward lower latitudes. The longest arrows point toward Asia, the shortest toward North America. The broken line north of Asia marks the edge of the continental shelf.

away from the east side of Greenland and from the region of the pole north of Greenland for a distance two or three times as great as the parting between Greenland and Labrador. These relations are roughly sketched in figure 6. It seems probable that the northwest coast of Nor-

[6] La Nature, January 21, 1905. Abstract in English: Literary Digest, March 18, 1905, pp. 396-397.

way was once united to the east coast of Greenland, although they are now over 1,000 miles apart, and the same may have been true of the northwest sides of Scotland and Ireland. There is less reason to think that the rifts on the sides toward Eurasia are wholly of Tertiary age; they may have been made partly at an earlier time, as suggested by Suess.

It may be noted that the greatest breadth of the Arctic Ocean, and probably of the parting from Greenland, is toward Asia, including the Aleutian arc. It is widest toward the island arcs of eastern Asia and toward the Malay earth-lobe and India. In figures 6 and 7 one can scarcely fail to see that the western coast of North America shows only faint, incipient arcs, corresponding to less crustal movement and the relatively narrow rift on the west side of Greenland, while on passing to the east coast of Asia the great island arcs bulge boldly into the depression of the Pacific, corresponding to a much more vigorous crustal movement and to a much wider rift between Greenland and Asia.

It is thus seen that the idea of a general crustal creep from high toward low latitudes in the northern hemisphere is borne out, not alone by the peripheral mountain ranges which fringe the southern border of Eurasia and the southwestern border of North America, but also by a rifting and pulling away of the earth's crust on all sides of Greenland, and that the amount of pulling away is least toward the feebler peripheral ranges and greatest toward the stronger.

The following are the faint peripheral arcs of North America: (1) The Alaskan Island arc, comprising the island chain of southeastern Alaska with Queen Charlotte and Vancouver Islands; (2) the Coast Range arc, extending from the Strait of Juan de Fuca to southern California, and (3) the Mexican arc, extending through Lower California and southern Mexico to the Isthmus of Tehuantepec. These arcs are shown in figure 7, but they are all faint and of slight curvature. They show much better in a map of North America drawn on spherical projection.

Suess has much to say concerning the remarkable correspondence of the Paleozoic and older sediments, and also of the mountain ranges on the two sides of the North Atlantic. He describes "The North Atlantic Continent" at some length (II, 220-255), and shows that it persisted until a very recent time in the earth's history. "We have recognized the existence of two continents, of which fragments only are visible at the present day. The first occupied the position of the north Atlantic Ocean, as is indicated by the nature and distribution of the Paleozoic sediments in Europe and America; Greenland is a remnant of it. This ancient continent is the *Atlantis*" (II, 254). Suess dwells upon the likeness of the Carboniferous sediments as being especially remarkable. The other fragmental continent referred to is Gondwana-land.

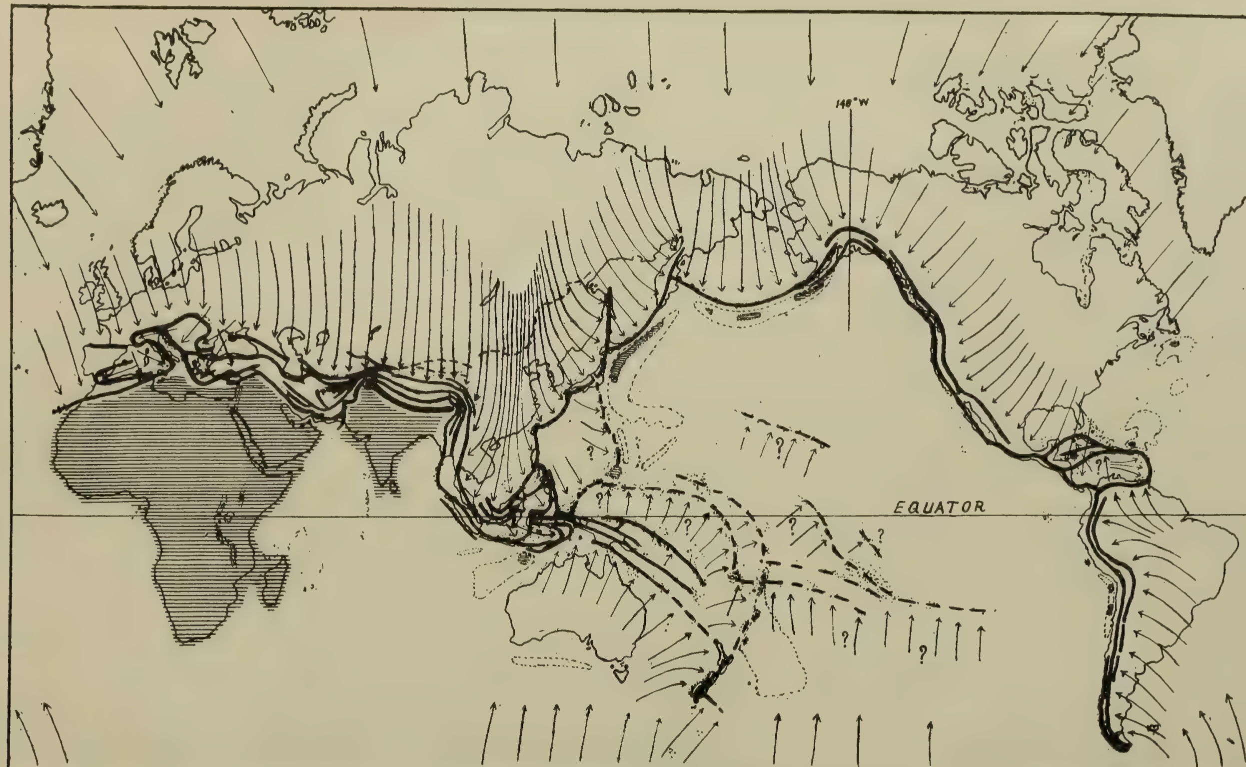

FIGURE 7.—*The World on Mercator's Projection*

Showing distribution of Tertiary mountain ranges in both hemispheres. The arrows indicate roughly the direction and relative amount of crustal movement. The map shows also the positions of the frontal oceanic deeps, the relations of the Tertiary ranges of Europe and western Asia to the Indo-African plateau, and the peculiar plan of the ranges between Asia and Australia and in the Caribbean region.

The recentness of the breaking up of Atlantis, as described by Suess, accords well with the conclusion that the rifts around Greenland are of recent date. The continent was pulled asunder apparently toward the southwest and southeast along a line passing southward from Cape Farewell and dividing around Greenland so as to leave it unmoved.

Penck, after enumerating many similarities between Europe and eastern North America, remarks that these similarities are not superficial.

> "In a very remarkable way these two sides of the Atlantic repeat the same structural features; there is an astonishing symmetry, as Eduard Suess has shown so clearly." "It is very interesting to see how the Appalachian region ends at Newfoundland, forming the projecting eastern corner of North America, and just opposite in south Ireland, in south Wales, in Cornwall, and in Brittany the belt of the old Hercynian Mountains of Europe begins. One seems to be the continuation of the other, and such an excellent geologist as Marcel Bertrand maintained that we have here to deal with the two ends of one very extensive belt of mountains which extended through the North Atlantic Ocean. But we must not forget that the missing link between both ends of these supposed mountain chains is longer than their known extent."[7]

No doubt some portion of each of these mountain chains is now submerged beneath the Atlantic. But it seems probable that a considerable part of the present oceanic interval is due to Tertiary and perhaps to older crustal movements which divided the original chain near Greenland and carried the parts away on divergent lines—to the southeast and the southwest. In a later work, referred to below, Suess again dwells particularly upon the remarkable similarities on the two sides of the Atlantic.

In the southern hemisphere South America appears to have crept away to the northwest and Australia to the northeast, but these two continents are nearly 180 degrees apart. Africa holds a medial position remotely suggesting a relation similar to that of Greenland to North America and Europe, but in reality the similitude fails, because Africa is tropical.

Tertiary crustal Movements in the Southern Hemisphere

AUSTRALIA

Passing by Africa and the Antarctic land, there are only two continents in the southern hemisphere, and they are relatively small. Present knowledge of them is rather meager.

In its continental type Australia resembles Asia. Both are roughly symmetrical in form, so far as relates to Tertiary diastrophism, whereas South America resembles North America, being unilateral or asymmetri-

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[7] Both passages from *Science*, February 26, 1909, pp. 322-323.

cal in form. The Tertiary fold lines of Australia and South America may be seen in figure 7. In these foldings the main body of Australia appears to have moved toward the northeast, but the movement was relatively feeble. All of its peripheral ranges are submerged in the ocean and are now represented only by chains of islands. New Guinea, New Zealand, and New Caledonia are islands of large size, but most of the islands are small. Between Australia and the equator there are three or four distinct lines trending mostly southeast to northwest. These lines are nearly straight, excepting that toward the northwest they turn to courses due west. Two or three of these lines run through New Guinea, one apparently extending southeast through New Caledonia. This line does not appear to connect with New Zealand. Another strong line runs through the Admiralty Islands, through New Mecklenburg, the Solomon Islands, New Hebrides, and eastern Loyalty Islands.

The alignment of the smaller islands is not clear in some parts, but one quite distinct line appears to begin north of the equator in the Egoi Islands of the western Caroline group, and, after running eastward 1,500 miles, sweeps in a great curve to the south through the Gilbert and Ellice Islands to the Fiji group, where it meets another line from the east. The greater size and height of the islands of the Fiji group as compared with those of the lines that enter it from the north and east reminds one of the island arcs of eastern Asia, where the points of intersection of the arcs are always higher than the arcs themselves, as in Kamchatka, Hokaido, and Formosa. Another line less clearly defined begins in the Marshall Islands, and appears to curve gradually around through New Zealand, the Phœnix, Tokelau, Samoan, Friendly, and Kermadec Islands. North of New Zealand there appears to be a line of narrow ocean deeps close along the east side of a submarine escarpment running from East Cape, New Zealand, to the Friendly Islands. This escarpment indicates folding from the west on the line of New Zealand produced, and it shows clearly that it is the Marshall-Samoa-Friendly line and not the Caroline-Gilbert-Fiji line which connects toward the south with New Zealand. New Zealand itself seems to owe its pronounced development to the junction of important lines, at least one to the northwest from the north island and one to the southeast from the south island.

The Hawaiian Islands, though so far away, appear to have a distinct affinity for the Australian lines southwest of them, and they appear to be just as distinctly independent of Asia and the Americas. The Washington-Christmas line lies farther south, with the same trend. The Samao-Society and Fiji-Cook-Austral lines run east-southeast, while the Taumotu and the Marquesas, on lines still farther east, trend to the southeast. They seem to show some affinity for Australia and at the same time are somewhat independent. Samao, like Fiji, seems to be a point of intersection for lines from the north and the east. These eastern lines seem to show no affinity for South America and very little for Australia, but are perhaps related more closely to a submerged crustal sheet lying to the south.

BORNEO, CELEBES, AND HALMAHERA

The peculiar mountain plans of these three islands have attracted the attention of geologists for more than a century, and the explanation of them has remained a puzzle. Their forms are shown in some detail in figure 8, but their relations to the trend-lines of the peripheral ranges are better shown in figure 2.

It will suffice for the present to point to the fact that they occur just where the advancing folds of Asia and Australia came into conflict (see figure 2). In each of these islands we seem to see a fold belonging to the southeast part of the Malay lobe advancing broadside against the end of one or more Australian folds, and both sets of folds are affected by the encounter. Celebes seems to show the simplest relations. The Malay fold appears to have been retarded and its trend-line indented by the Australian fold, while the Australian appears to be broken and reflected back. The mechanics of these forms, however, are not yet clearly understood.

The plan of Borneo strongly resembles that of Celebes, but it has been elevated so that its platform is above the sea. Halmahera is also a miniature of the same type.

Another point illustrated here is that where the Tertiary belt has several ranges, not only were the back ranges made first, but during the later folding of the front ranges the back ranges were subjected to a movement of elevation without further folding. Borneo is largest and highest, Celebes smaller and lower, and Halmahera still more reduced. We seem to see also a dying out of intensity from Borneo to Halmahera. Is it not significant that these strange forms occur just here at the point of conflict between the Tertiary mountain belts of Asia and Australia?

Suess calls these forms "chiragratic," and places Chalcidyce and Morea of the Dinaro-Tauric arc in the same class (I, 506). The latter are peculiar, but they are not the same as the Malay forms, and were not produced in the same way—that is, by a broadside-to-end conflict of folded ranges.

SOUTH AMERICA

In the present state of knowledge there is not much to say about this continent, for it is decidedly the most abnormal of any that were affected

FIGURE 8.—*East Indian Archipelago*

Showing the peculiar mountain plans of Borneo, Celebes, and Halmahera, and their relations to the fold-lines of Asia and Australia.

by the Tertiary tangential movements. Its crustal movement was deflected to the west even more strongly than was that of North America—more strongly than any other continent, unless it be the New Zealand part of the Australian sheet (see figure 7). Only in the extreme northern part was the movement northward. A part of its Tertiary chains in Peru and Bolivia trending northwest and southeast were thrust from the northeast, and have therefore been deflected more than 90 degrees from the normal south-to-north direction, and the same is the case with New Zealand. The great arc of the northern Andes, extending from Venezuela to northern Chile, is convex toward the west—that is, toward the Pacific.

Here again the Cuzco knot of the Andes, one of the most remarkable mountain knots in the world, is somewhat interlobate in character—that is, it is in a re-entrant angle, where the crustal movements were slightly convergent, though less so than in Alaska. The Alps of New Zealand appear also to be at an angle of convergence or intersection.

The most peculiar character in South America, however, is the curvature of its Cordillera to the east at the southern extremity. It is as though the folds of the main Cordillera, being pushed toward the west, had lagged or dragged behind the rest at the extreme southern end. If this be true, it appears to indicate a minimum movement of 400 or 500 miles, which compares favorably with the movement of North America, as indicated by the rift of the Labrador Sea.

The curved ranges of the Antilles lie in the region of conflict between the two Americas, just as the irregular ranges of Europe lie between Europe and Africa and the peculiar mountain forms of Borneo, Celebes, and Halmahera lie between Asia and Australia. But the movements of the two Americas did not meet squarely, nor was one much more vigorous than the other. Both being relatively weak, there was an easier adjustment on curves of broader sweep. Nevertheless, the magnificent curve of the lesser Antilles reminds one of the sharper curves in Europe—the Roumanian, Alpine, and Betic arcs—and still more of the sharp curves of the Java and Timor lines, where they turn in such remarkable curves from east to north and back to the west to the island of Ceram (see figure 2). Even if the explanation of the plan of these ranges be regarded as still problematical, it is easy to see that they all occur in regions where there was a conflict of crustal movements and a tendency to a tangling and complication of folds.

THE MID-ATLANTIC RIDGE

One of the most remarkable and suggestive objects on the globe is the mid-Atlantic ridge. It is well shown on Sir John Murray's bathymetri-

BATHYMETRICAL CHART OF THE OCEANS

After Sir John Murray

cal chart of the oceans, referred to above, and that part of the chart showing the ridge is reproduced here in plate 4.

The persistence with which this feature maintains a medial position in the ocean bed for nearly 9,000 miles (following its great curves) is very striking, and the position which it takes in passing between South America and Africa is still more remarkable. The ridge is a submerged mountain range of a different type and origin from any other on the earth. It is apparently a sort of horst ridge—a residual ridge along a line of parting or rifting—the earth-crust having moved away from it on both sides. On the chart it is indicated to be mostly less than 2,000 fathoms (12,000 feet) beneath the sea, with some parts less than 9,000 feet and a few volcanic islands which rise 3,000 or 4,000 feet above the sea. Its general height above the surrounding ocean floor is between 3,000 and 6,000 feet, with a few island peaks rising 18,000 or 20,000 feet. Between South America and Africa the ridge runs east-southeast through 40 degrees of longitude (nearly 3,000 miles), and in this part is parallel with the adjacent continental border of South America.

The great westward bulge of Africa north of the equator appears to fit very closely into the westward bend of the mid-Atlantic ridge, suggesting that Africa has drifted eastward from that position. All authorities seem to agree, however, that Africa did not participate in the Tertiary folding, but remained stationary. Hence, if its western margin ever rested on the mid-Atlantic ridge it can hardly have been at a later time than the Carboniferous, for no important or extensive crustal movements appear to have affected Africa since that time. Too little is known of the geology of Africa, however, for settled conclusions now, but the narrow belt of peripheral folds on the southeastern border and also the high plateau of eastern Africa seem to be normal products of a crustal movement from the west-northwest.

At a first glance, the mid-Atlantic ridge appears to favor the torsion hypothesis of Prinz,[8] in which the southern hemisphere is supposed to have been rotated to the east relatively to the northern. The ridge certainly seems to suggest such a movement more definitely and precisely than any other feature yet described, but its form would seem to indicate that the yielding to the torsionary force was confined to a narrow zone near the equator, and that in that zone it had caused a displacement of nearly 3,000 miles. If the ridge ran originally straight north and south, and has been offset by torsion to give it its present form, then a section

[8] Dana's Manual of Geology, 4th ed., pp. 395-396. Also Bulletin of the Geological Society of America, vol. 11, 1899, pp. 93-94.

of it about 1,000 miles long has been stretched to a length of nearly 3,000 miles!

It is probably much nearer the truth to suppose that the mid-Atlantic ridge has remained unmoved, while the two continents on opposite sides of it have crept away in nearly parallel and opposite directions. The Cordillera of South America show that that continent moved a considerable distance toward the west and northwest in the Tertiary diastrophism; the movement of Africa appears to have occurred at a much earlier date, apparently before the Mesozoic era.

There are many bonds of union which show that Africa and South America were formerly united. Their present forms and relations suggest that the force which parted them was one that tended originally to crowd the two parts toward each other—that is, it tended to make Africa move south and South America north. But the release of strain was found by a great diagonal fracture along which the crust divided in two parts that crept away in opposite directions. The mid-Atlantic ridge remained unmoved and marks the original place of that great fracture.

THE ANTARCTIC LAND

This is the great southern horst, just as Greenland is the great northern, but its rôle in the Tertiary movements appears on present knowledge to have been less prominent. The pulling away from the Arctic regions was prodigious, especially toward Asia; only Greenland remained unmoved; whereas the whole of the Antarctic land appears to have held fast, while only Australia and South America pulled away. No doubt great rifts exist, corresponding to the pulling away of these two continents, but they appear to be submerged and obscured much more than those of the north. Perhaps the Jeffreys deep, south of Australia, stands in this relation to that continent, and possibly the Ross deep bears the same relation to Scuth America.

THE SOUTHERN HEMISPHERE THE COMPLEMENT OF THE NORTHERN IN TERTIARY CRUSTAL MOVEMENTS

Although the facts are fewer and perhaps not so clear in their import, there seems still to be ample evidence that, excepting the southern part of the Malay arc, those parts of the Tertiary mountain belt which fall within the southern hemisphere were produced by crustal movements which were directed in general from south to north or in the opposite direction from those of the northern hemisphere.

The abstract statement made above may now be extended so as to include the whole earth, thus: In the Tertiary mountain making the crustal sheets moved in general from high toward low latitudes in both hemispheres—that is, both polar areas were regions of crustal dispersion or spreading, and the continental sheets, excepting Africa, all crept toward the equatorial zone. Hence the general order or plan of deformation was the same for both hemispheres, and the two complementary halves taken together make a symmetrical whole.

Distribution of the deforming Force

If the foregoing conception of the manner of production of the Tertiary mountain ranges be erroneous it is, of course, useless to seek an explanation of the earth's plan by this means. It may be said, however, for this conception that it is built upon a foundation consisting solely of observed facts, without any dependence upon a preconceived idea of the cause of the crustal movements, and yet it reveals, in the distribution of the Tertiary mountain belt and in characters which show the relations of the several parts of that belt to the continental crustal sheets, a degree of systematic order and unity not reached by other methods, and this alone seems to justify further consideration.

It is worthy of note that no other great crustal movements than those described above appear to have occurred in the Tertiary diastrophism. Indo-Africa was not affected by tangential movement. If it was affected at all it moved only radially—that is, either up or down. There appear to be conflicting evidences on this point, but the great rift valleys of the lake region in Africa suggest moderate uplift. These valleys are roughly meridional and suggest a slight girth-expansion of the earth. This effect, however, is relatively small, and for the present purpose is negligible. The tangential movements affecting the other continents may therefore be taken as a substantially complete inventory of Tertiary deformation.

The facts of distribution seem to show plainly that the deforming forces were in some way conditioned by latitude, for vast crustal sheets moved toward lower latitudes from both poles, and these movements appear to have satisfied largely the stresses caused by the deforming forces. The effect appears to be the same as if the deforming forces had operated to flatten the earth at the poles. If Africa were slightly uplifted without tangential movement, this uplift and the meridional rifting may be an effect of equatorial bulging or girth-expansion. But whether Africa shows equatorial expansion or not, the remainder of the continents surely show polar flattening and crustal dispersion. The deforming force appears to have acted with maximum power in high latitudes, for the mountain ranges produced by the Tertiary crustal movements are found mainly in middle and low latitudes—that is, along the lower margins of the crustal sheets.

Relation of the Tertiary crustal Movements to the Earth's Plan

Enough has been said in the preceding pages to show how the present plan of the earth has been affected by the Tertiary crustal movements. All the continents excepting Indo-Africa were affected and modified by them. As Suess observes, all the older parts of the continents were subjected to folding before the Tertiary, and yet it is certainly true that the Tertiary movements dominate largely in the earth's present plan and have given all the continents the larger part of their present outlines, excepting Indo-Africa.

One of the most remarkable things in the earth's plan is the fact that so much land appears to be clustered around the north pole and so little around the south pole. The northern hemisphere is largely continental, while the southern is mainly oceanic. In the northern hemisphere, however, Greenland is the only large remnant of the original north polar continent and most of the polar region is open sea, much of it deep, while in the southern the pole and the polar regions generally are occupied by the Antarctic continent, which is many times larger than Greenland. These peculiarities have not been explained, but if flattening of the poles with crustal dispersion characterized the Tertiary deformation as described above, then a simple explanation seems available.

Suppose the earth to have been originally a perfect sphere, and then to have been subjected to polar flattening, like that described above and suggested by Suess himself in one of his later works. This would change the earth to an oblate spheroid. The polar flattening, with a tendency to crustal dispersion, may be supposed to affect both poles at once and at first equally.

Now the first pole to undergo a crustal movement toward lower latitudes on a large scale would manifestly cause a slight shifting of the earth's center of gravity toward the other pole. Suppose the first large movement to have been from the north pole, then the earth's center of gravity would be shifted slightly toward the south pole. This would leave the remaining north polar lands under slightly greater strain than before, while the strain tending to dispersion of south polar lands would be proportionally diminished.

Such a change would, of course, increase the chances of further movements from the north pole and decrease those from the south pole. Thus the pole from which the first great movement occurred would take the lead in crustal movements, and would continue henceforth to be the one from which the greatest movements would take place. The ocean would follow the shifting center of gravity, and thus would tend to draw away slightly from the north polar regions and rise slightly upon the south polar regions. Both of these effects tend to a concentration of land around the north pole and of water around the south pole. The stronger crustal creep from the north pole appears to have carried the land away from the immediate vicinity of that pole, while the feebler dispersion from the south pole has left a high, extensive land-mass in that region.

The southward tapering of the continents may also be related in some way to the dominance of crustal movements from the north pole. The strong dispersion from this pole and the drawing away of the water has left a girdle of land near the Arctic circle which is continuous, except for the narrow Bering Strait and the wider rifts on the east and west sides of Greenland. Even if the entire surface of the globe north of the 45th parallel of north latitude had been land at the beginning of the Tertiary movements, and if all the crust of this area had crept away southward into latitudes lower than the 45th parallel, it could not have filled the space south of this parallel with land, because of the great increase of area. At the same time, the north polar flattening appears to have been confined almost wholly to the area north of the 45th parallel. Hence, in moving southward there was a diminishing power of the deforming force and at the same time a very large increase of surface area. In these two circumstances there are elements which necessarily imposed limitations upon the southward extension of the continents, but they seem to suggest broad lobate forms like Asia and Australia, rather than tapering, pointed forms like North and South America. But the American and African forms may have arisen from the influence of preexistent meridional faults or lines of weakness which drew the crustal movements to one side.

Suess on the Cause of Deformation of Strand-lines

It does not fall within the scope of this paper to attempt any discussion of the ultimate causes of the Tertiary mountain making, nor of the more recent displacement of the strand-lines, but any suggestion by Suess upon these points is worthy of the most careful consideration. Because he has reviewed the field more extensively and more thoroughly than any other living man, we are naturally inclined to look to him more than to any one else for an explanation of the causes of displacement of strand-lines and of mountain making. But Suess does not undertake to explain. He is content to make only very brief and apparently tentative suggestions concerning the nature of the causes.

It is interesting to observe that after relying upon eustatic negative movements through nearly all of part III of "The Face of the Earth" to account for displaced strand-lines, Suess turns in the closing pages of that part to a very different cause, where he says:

"Movements like these, which present themselves as oscillations, and extend around all coasts and under every latitude in complete independence of the structure of the continents, can not possibly be explained by elevation or subsidence of the land. Even as the transgressions of the ancient periods are much too extensive and uniform to have been produced by movements of the lithosphere, so, too, are the displacements of the strand-line in the immediate past" (II, 550).

After rejecting Adhémar's suggestion of an alternating accumulation of water at each of the poles, he observes:

"As far as we are in a position to judge, it appears much more as if that which characterized the more recent movement was an accumulation of water toward the equator, a diminution toward the poles, and as though this last movement were only one of the many oscillations which succeed each other with the same tendency—that is, with a positive excess at the equator, a negative excess at the poles.

"Negative traces are to be seen in all latitudes. We may attempt to explain them by means of eustatic negative processes—that is, by great subsidences; but this would presuppose a uniform sinking of the sealevel to the extent of more than 1,000 feet in quite recent times. It is much more probable that the negative traces at considerable altitudes in the tropics are not of the same age as those in high latitudes, and that an accumulation of water occurs alternately at the poles and the equator. Among these traces there may be one or more of a eustatic negative origin, but if so, we have not yet learned how to distinguish them" (II, 551).

Thus, although he had relied in earlier chapters almost exclusively upon subsidence as the one great agency of change in the earth's history, Suess seems constrained to admit in the last analysis that most of the displaced strand-lines appear to have been caused by an independent oscillatory movement of the ocean. Suess calls this movement an oscillation; but what kind of an oscillation is it? He answers this question clearly enough, where he says that "an accumulation of water occurs alternately at the poles and the equator."

The present figure of the ocean is that of an oblate spheroid—a spheroid having a certain degree of oblateness which is roughly expressed by the fact that the polar diameter of the globe is 26 miles shorter than the equatorial diameter. If the present phase of oscillation is one in which, as Suess says, there is an accumulation or positive excess of water at the equator and a negative excess at the poles, then the climax of the next preceding phase was one in which the positive excess was at the poles and the negative at the equator, and the degree of oblateness was less than it is now. Suess does not give a name to the oscillation which he describes, but he might as well have done so, for obviously it is merely an oscillation of the oblate figure—that is, a change from one degree of oblateness to another and back again, repeated time after time. The latest change, according to Suess, was an increase of oblateness.

The case could not be more clearly or forcefully stated than it is by Suess, so far as relates to the ocean. But he stops there. Yet, how is it possible to confine a force which changed the figure of the sea to the sea alone? The same force must have been exerted at the same time and with the same power upon the land—that is, on the lithosphere or solid globe. And if it were, what would be the nature of the stresses set up and what movements might be expected when those stresses were relieved?

Manifestly, on Suess' idea the present surface of the ocean is lower in the polar regions than it was some time in the relatively recent past and higher at the equator. The new figure intersects the old on a parallel a little below the 45th in both hemispheres. The lands in the far north therefore stand relatively higher above the sea, or rather above the ideal mean surface plane of the solid globe,[9] than before and at a slightly different angle to this plane at all points, excepting at the poles and the equator. In middle latitudes there is a slight change of angle, but no appreciable change of altitude.

Any imaginary plane or surface which before the change lay parallel with the surface of the sea in northern latitudes would now have the appearance of slanting slightly downward toward the south. It would seem certain that such a change as this would be fraught with tremendous consequences to the solid globe, for the relative increase in altitude of all lands in high latitudes would disturb the preexisting equilibrium and increase the stresses in those lands tending to subsidence. But the earth being solid from its surface to its center, and more rigid than the hardest steel, the tendency to sink directly toward the center could not be realized. The more rigid central body would resist effectively, and the forces would consequently be deflected from inward radial to tangential forces radiating from the pole and affecting only a relatively

[9] Estimated by Gilbert, on data collected by Sir John Murray, to be about 9,000 feet below sealevel. In his International Geography, H. R. Mill puts it at about 7,500 feet,

thin crust. These forces would tend to cause the crust to creep away on lines of dispersion from the pole.

An imaginary plane, like that mentioned above, gently sloping toward lower latitudes and situated beneath the earth's crust just within the zone of rock flowage, would seem to afford a basal slope down which the crustal sheets might move, and the tangential thrust forces exerted in the crust toward lower latitudes would tend to give the crust the requisite impulse to move.

We may thus enumerate, in part, the conditions and the tendencies to earth-movements which might be expected to affect the lithosphere on the supposition of a flattening of the poles, like that postulated by Suess in explanation of displaced strand-lines.

Conclusion

The displacement of strand-lines by eustatic negative movements is a very different thing from displacement by oceanic oscillations. As was pointed out above, it is only at the end of his exhaustive review of the whole subject that Suess recognizes and accepts the principle of oceanic oscillation. After accepting this principle in explanation of the strand-lines, it seems a little strange that Suess should have made no mention in "The Face of the Earth" of the possibility that the same force which caused oscillation of the ocean might be a cause of crustal movements also; but there appears to be no suggestion of this idea, at least not in the first four parts.[10]

In a later work, however, Suess seems to see the possibility of deformation of the lithosphere by a force that flattens the poles in the same manner as he supposes oscillations of the ocean to do for the strand-lines. He says: "One is inclined to suspect that the formation of the curved chains in Asia, open to the north, stands in some connection or other with the outflow of superfluous earth-mass from the pole—that is, with a flattening of the same."[11]

Perhaps these words are not sufficiently explicit to enable one to say that Suess accepts the idea that the forces associated with an increased oblateness of the earth's figure are the cause of polar flattening of the lithosphere, but it is hard to see how he could have had any other cause

[10] Volume IV, containing Part V of Suess' "Face of the Earth," reached the writer a few days before the proof of this paper. A hasty examination disclosed nothing that suggests any important change in the conclusions reached. Chapters VII, IX, X, XI, XIV, XVI, and XVII are of particular interest in connection with this paper.

[11] E. Suess: Asymmetry of the Northern Hemisphere. Appendix to the presidential address of B. K. Emerson. Bulletin of the Geological Society of America, vol. 11, 1899, p. 105. Published in German in 1898.

in mind. Whatever the cause may have been, its distributive characters appear to be precisely the same as those which belong to an increase of oblateness of the oceanic figure. Why should we look for two separate causes for two sets of phenomena which appear to require precisely the same kind and distribution of force to produce them?

The first author to suggest oscillations of the figure of the ocean as the cause of displaced strand-lines appears to have been Emmanuel Swedenborg. Suess traces this idea back to him through Robert Chambers and P. Frisi (II, 7, 11, 16, and 21). But whether Suess regards increased oblateness as the cause of crustal movements or not, it seems certain that he would have reached this conclusion long ago if he had held steadfastly to his first conception that the mountain ranges of western North America were folded toward the Pacific, instead of receding from that position in deference to the contrary opinions of certain American and Canadian geologists; for if he had found North America folded toward the Pacific Ocean, he would also have found that the evidence of general crustal creep and dispersion from high toward low latitudes is complete for the northern hemisphere.

All forms of the contraction hypothesis meet with two insurmountable difficulties with reference to the Tertiary period of mountain making. They fail to explain in a satisfactory way the distribution of Tertiary mountain ranges upon the earth's surface, and they do not explain how so great a period of mountain making could have occurred in so recent time. If due to contraction arising from cooling, it is necessary to suppose a very long period of accumulation and storage of mountain-making force before the beginning of the folding movement. The amount of crustal movement which occurred during the Tertiary period seems to be far in excess of the most that can be attributed to cooling and shrinking since the time of the Permo-Mesozoic (Appalachian) folding, even on the most liberal estimate. It is scarcely credible that any considerable mountain-making force derived from cooling before the time of the Permo-Mesozoic folding could have survived that event so as to be an important element in the Tertiary folding.

Referring to the tangential crustal movements in Asia, Willis, in a recent development of the contraction hypothesis based on isostacy, says: "What Suess considers an outward advance, I regard as a retarded superficial layer, beneath which the deeper mass has been squeezed northward into narrower space."[12] Willis supposes subsidence of the earth-segment under the Pacific and Indian Oceans, with northward spreading or un-

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[12] Bailey Willis: Research in China, vol. 2, Systematic geology. Carnegie Institution of Washington, 1907, p. 126.

derthrusting of the deep-seated mass beneath Asia. By this hypothesis the crustal sheet in which the folding, overthrusting, etcetera, are produced is not the part in which the principal movement occurs. The crustal sheet is regarded as a passive element, and the mountains of Asia exist only because some other part of the earth than the crust moved horizontally and the crust became involved in that movement. But if the same results in mountain making can be derived from horizontal movements of the crust alone, why postulate a more complicated indirect process?

Even Chamberlin's Planetesimal hypothesis, which has brought so great an advance over the Nebular hypothesis of Laplace with reference to the origin and growth of the earth, meets these same two difficulties, and with no better success.[13]

It seems certain that no man living has ranged so widely over the fields of geology for the entire earth as Eduard Suess. He appears to have made himself familiar with every official report and every important memoir or scientific contribution that has ever been written on the subject. His earlier studies turned his mind along certain lines of interpretation, chiefly depression of oceanic basins and tangential crustal movements overthrusting those basins. This was natural, for every one must arrange his thoughts around some central idea as he goes on working year after year, decade after decade. Indeed, one's thoughts will inevitably crystallize themselves around some uniting principle, whether he will or no. These early principles of interpretation served Suess well throughout the greater part of his life. But is it not deeply significant that after a lifetime of study along the lines of those early principles, Suess at last leans toward a different interpretation, both as to the cause of displaced strand-lines and of deformations of the lithosphere? And is it not still more significant that in both instances his leaning is toward a cause which conforms precisely with increased oblateness of the earth's figure, or with oscillations of the same?

The argument presented in this paper rests at last on the truth of Suess' interpretation of the mountain plan of Asia. The principles which he worked out there have been applied without important modification to the other continents, and the conclusions reached in this way appear to accord very closely with suggestions made by Suess himself in his later writings. For a change in the degree of oblateness, either in oceanic oscillations or in deformations of the lithosphere, one is inclined to reject all internal causes and to look to some form of tidal force as the only possible agency.

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[13] Chamberlin and Salisbury: Geology, vol. ii, pp. 82-132.

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ISOBASES OF THE ALGONQUIN AND IROQUOIS BEACHES, AND THEIR SIGNIFICANCE[1]

BY JAMES WALTER GOLDTHWAIT

(*Read before the Society December 28, 1909*)

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INTRODUCTION

The study of epeirogenic movements by means of critical surveys of raised beaches is one for which North America is a peculiarly rich field. The investigations of Gilbert in Lake Bonneville, of Upham in Lake Agassiz, and of Gilbert, Spencer, Leverett, Taylor, Fairchild, Coleman, Woodworth, and others in the Great Lakes region have contributed greatly to the understanding of post-glacial upwarpings. Among the many papers which have been written on this subject, one is unique in that it seeks to correlate observations over all eastern North America. This is the paper read before the Boston Society of Natural History in 1892 by Baron Gerard De Geer.[2]

[1] Manuscript received by the Secretary of the Society January 12, 1910.

[2] Gerard De Geer: On Pleistocene changes of level in eastern North America. Proceedings of the Boston Society of Natural History, vol. 25, 1892, pp. 454-477.

This distinguished visitor, fresh from studies of the upwarped marine strands of Scandinavia, applied himself at once to the task of correlating the measurements of raised beaches which had been made in New England, the maritime provinces, the Great Lakes region and the Northwest; and this correlation he reinforced with hurried though accurate observations of his own in New England and southeastern Canada. In order to show the upwarped form of the old "geoid surface" which he reconstructed, De Geer used a device which Gilbert had used ten years before in connection with Lake Bonneville[3]—he drew curves of equal deformation of the ancient water-plane. These he named "isanabases," or "isobases."[4] They were not limited to the Atlantic Coast district which De Geer had personally examined, but were extended far into the interior, on the basis of measurements already secured around the Great Lakes by Gilbert, Spencer, Upham, and Todd, and in Labrador and the Hudson Bay region by Bell and Low. In view of the scarcity of data which De Geer had at his command and of the difficulties in correlation which he met by "interpolating" his geoid surface beneath deformed lake beaches of unknown ages, it is no wonder that his isobases for the Great Lake region hit wide of the mark. It would hardly have been surprising if his conclusions had been thoroughly discredited by later detailed investigations. On the contrary, however, De Geer's most fundamental conclusions seem to have been confirmed. The analogy which he drew between the North American and the Scandinavian uplifts appears to hold good; in both cases the movements were differential uplifts of a glaciated area, and in both the isobases follow so closely the boundary of pre-Cambrian areas that a causal connection between pre-Cambrian oldlands, glaciation, and differential uplift is strongly suggested.

Since De Geer's map was published, the use of isobases seems to have been limited almost wholly to private studies; very few isobasic maps have been published, and even these concern districts of comparatively small extent. This has probably been due in most cases to the fact that measurements have not been numerous or accurate enough to make the isobases convincing, or even passably satisfactory. The fault has been in the data rather than in the method. One can easily see that an isobasic map is as valuable to the investigator of epeirogenic movements as a contour map is to the physiographer. If the data which we possess are too

[3] G. K. Gilbert: Contributions to the history of Lake Bonneville. Second Annual Report of the U. S. Geological Survey, 1882, pp. 195-197, plates xlii and xliii.

[4] Gerard De Geer: Quaternary changes of level in Scandinavia. Bulletin of the Geological Society of America, vol. 3, 1892, p. 66; and op. cit., Proceedings of the Boston Society of Natural History, vol. 25, 1892, p. 457.

incomplete to justify the drawing of isobases, our efforts ought to be redoubled to accumulate data so accurate and so abundant that a set of isobases shall provoke no more skepticism than so many well-executed contour lines. Then, and not until then, can we hope to do much in analyzing the great upwarpings of late glacial time.

Good isobasic maps are valuable in two ways: First, as aids to fixing the relative ages of extinct lakes in different parts of a region; and, second, as indicators of the extent, nature, and cause of epeirogenic movements. The present paper touches both sides of the subject. Isobases for the Iroquois beach and the Algonquin beach will be compared, with a view to answering the question whether these two critical stages of the extinct lakes, Iroquois and Algonquin, are synchronous or not. The question of the nature and cause of the differential uplifts will be treated very briefly, because that is soon to be taken up by Mr. F. B. Taylor in a monograph which is now in preparation.

The data here used are from several sources, as references in every case will show. Most of the measurements of altitude of the Algonquin beach have been made during the last five years by the geological surveys of Wisconsin and Michigan, the U. S. Geological Survey, and the Geological Survey of Canada. These measurements are especially reliable, because they were made with the wye-level, rather than the hand-level or the aneroid barometer.

The Algonquin Water-plane

STAGE RECORDED BY THE ALGONQUIN BEACH

The Algonquin beach marks a critical stage in the history of Lake Algonquin. For some time previous the discharge of the ice-dammed lake had been entirely through the Trent Valley into the waters of the Lake Ontario basin along the "Algonquin River"[5] (see figure 1). Differential uplifts, however, had been lifting this region with respect to more southerly districts, and the rising waters of the lake had been advancing on the shores in the Michigan and Huron basins. When the head of the Trent Valley, at Kirkfield, Ontario, had been lifted to an altitude as high as the pass at the south end of Lake Huron, that pass began to receive a share of the overflow which ran down the Saint Clair and Detroit rivers into Lake Erie. This two-outlet stage of the lake is

[5] The names "Lake Algonquin," "Algonquin beach," and "Algonquin River" were first used by J. W. Spencer: Notes on the origin and history of the Great Lakes of North America. Proceedings of the American Association for the Advancement of Science, vol. 37, 1889, p. 199.

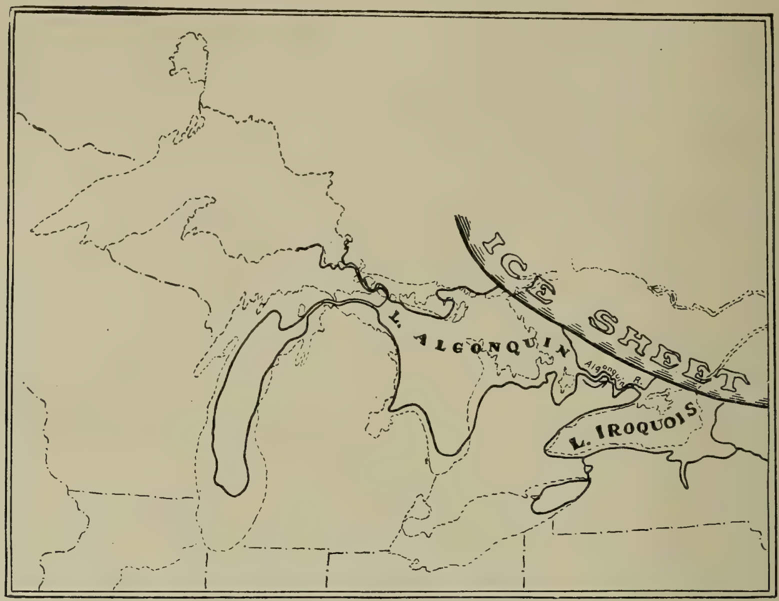


FIGURE 1.—*Map of Lakes Algonquin and Iroquois*

A short time previous to the date of construction of the Algonquin beach. (After Gilbert)

FIGURE 2.—*Map of Lake Algonquin*

At the stage marked by the Algonquin beach. The existence of Lake Iroquois at this time is doubtful. The position of the ice border is quite hypothetical the stage marked by the Algonquin beach (see figure 2). It lasted probably but a short time, for as the canting of the region proceeded the discharge was shifted entirely into the Saint Clair River, while the Trent Valley and surrounding shores of the lake emerged from the water. Thus a beach which had been under construction perhaps for centuries, during the regime of the Algonquin River and the slow rising of Lake Algonquin, was suddenly abandoned as the water-plane adjusted itself to the new outlet. The canting of the abandoned water-plane progressed until the beach at Kirkfield had been lifted 275 feet higher than it had stood during the two-outlet stage.[6]

Today the Algonquin beach can be followed somewhat continuously from the old outlet at the head of the Saint Clair River, where it stands 607 feet above sealevel,[7] to the head of the more northerly outlet at Kirkfield, where its altitude is 883 feet. From here down the Trent Valley the course of the ancient Algonquin River is marked by a chain of extinct lakes and rapids which terminated in the contemporary waters of the Lake Ontario basin.[8]

ISOBASES OF THE UPWARPED PORTION OF THE ALGONQUIN PLANE

On the isobase map (plate 5) about 100 localities where the altitude of the Algonquin beach has been accurately determined are shown by round dots. In about 60 of these cases the measurements themselves are indicated in feet above sealevel. They are as follows:

Locality	Altitude, feet	Authority
West side of Lake Michigan:		
Burnt Bluff	723	W. H. Hobbs, Michigan Geological Survey, 1907.
Deaths Door	660	J. W. Goldthwait, Wisconsin Geological and Natural History Survey, 1905.
Rowleys Bay........	654	Ditto.
Oconto	620	Ditto.
Sturgeon Bay	621	Ditto.
Cormier	611	Ditto.
Algoma	610	Ditto.
Two Rivers	607	Ditto.
Evanston	605	J. W. Goldthwait, 1906.
Rogers Park	604	Ditto.

[6] This sequence of events was first recognized by J. W. Spencer, loc. cit. It has been confirmed by observations of Gilbert and Taylor.

[7] Since Saint Clair River became the sole line of discharge of the lake, it has been deepened enough to lower the level of the waters in the Huron basin from 607 feet to 581 feet above sealevel.

[8] Gilbert: The Algonquin River (Abstract). American Geologist, vol. 18, 1896, p. 231.

Straits of Mackinac and east side of Lake Michigan:

Hessel	863	F. B. Taylor and J. W. Goldthwait, U. S. Geological Survey, 1907.
Mackinac Island	812	Ditto.
Cross Village	746	Ditto.
Beaver Island	731	Ditto.
Harbor Springs	709	Ditto.
Norwood	674	Ditto.
Northport	658	Ditto.
N. Manitou Island	648	Ditto.
Traverse City	619	Ditto.
Frankfort	605	Ditto.
Herring Lake	607	Ditto.
Arcadia	603	Ditto.
Muskegon	604 (?)	Ditto.
Spring Lake	603	Ditto.
Holland	604	Ditto.

West side of Lake Huron:

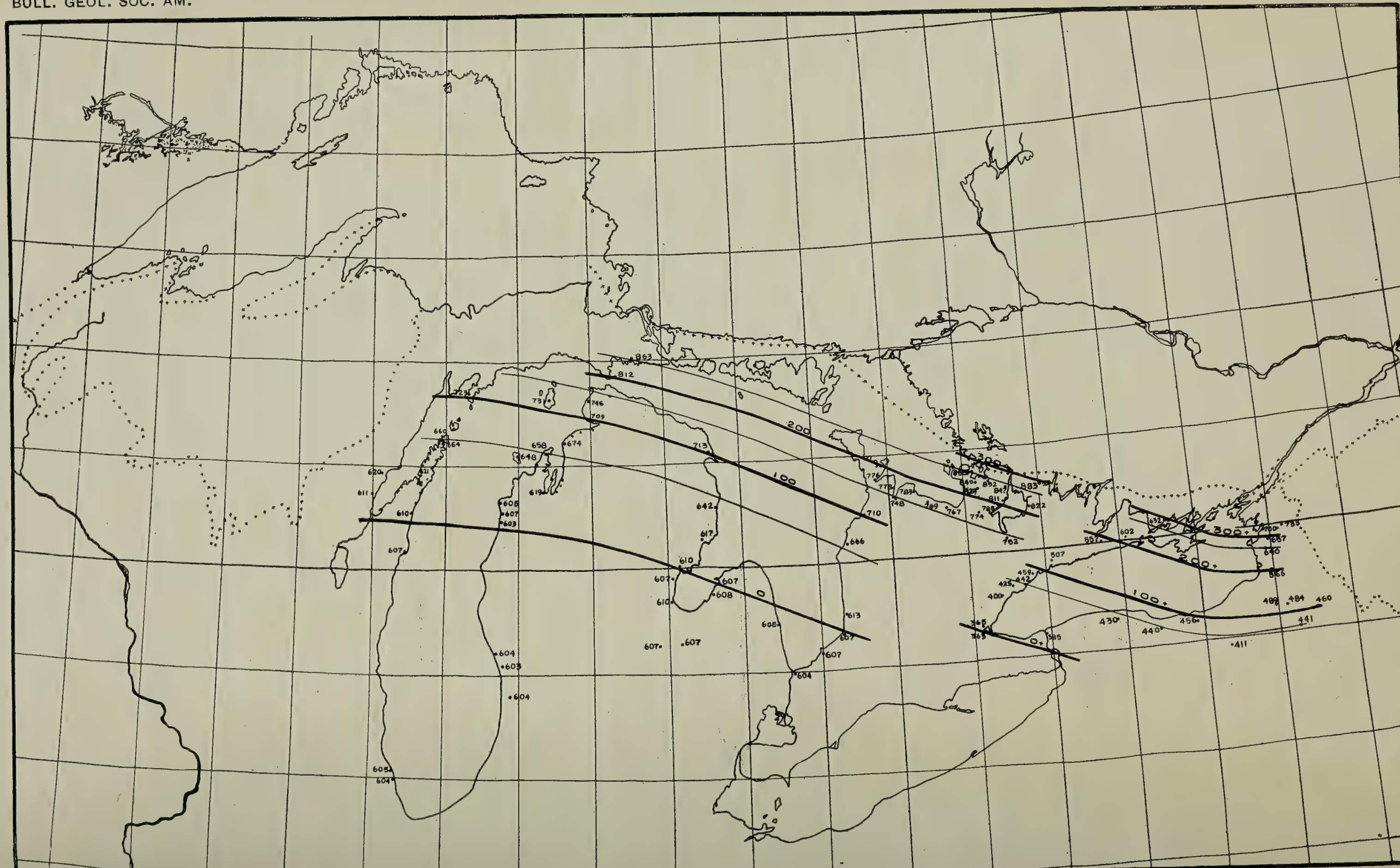
Alpena	713	Frank Leverett, U. S. Geological Survey.
Greenbush	642	Frank Leverett, Michigan Geological Survey, 1901.
Tawas	617	W. M. Gregory, Michigan Geological Survey, 1901 and 1907.
Omer	610	Ditto.
Worth	607	Ditto.
Kawkawlin	610	W. F. Cooper, Michigan Geological Survey, 1905.
Bayport	607	A. C. Lane, Michigan Geological Survey, 1900.
Sebewaing	605	Ditto.
Bridgeport	607	W. F. Cooper, Michigan Geological Survey, 1908.
Saint Charles	607	Ditto.
Port Sanilac	605	Ditto.

East side of Lake Huron:

Port Elgin	710	F. B. Taylor and J. W. Goldthwait, Canadian Geological Survey, 1908.
Kincardine	666	Ditto.
Bayfield	613	Ditto.
Grand Bend	607	Ditto.
Kettle Point	607	Ditto.
Sarnia	604	Ditto.

Georgian Bay and Penetang Peninsula:

Wiarton	776	Ditto.
Hogg	778	Ditto.
Owen Sound	748	Ditto.



ISOBASIC MAP OF THE ALGONQUIN AND IROQUOIS BEACHES

Showing the broader features of warping

Georgian Bay and Penetang Peninsula—Continued:

Meaford	783	F. B. Taylor and J. W. Goldthwait, Canadian Geological Survey, 1908.
Clarksburg	769	Ditto.
Mair Mills	767	Ditto.
Colwell	774	Ditto.
Penetang	855	Ditto.
Wyebridge	840	Ditto.
Elmvale	829	Ditto.
Coldwater	852	Ditto.

Lake Simcoe district:

Orillia	847	Ditto.
Oro	811	Ditto.
Barrie	785	Ditto.
Holland Landing	752	Ditto.
Beaverton	822	Ditto.
Kirkfield	883	Ditto.

With hardly an exception these measurements were made with the wye-level.

In regard to the data from localities east of Lake Huron and Georgian Bay, it should be said that the altitude of the Algonquin beach at most of these places was measured by Dr. J. W. Spencer in 1887. With only two or three exceptions the new measurements of 1908 agree with those of Spencer, and bear witness to the accuracy of his work.

Isobases for every 50 feet of uplift between 0 and 300 have been drawn with reference to these localities. That the isobases accord properly with the 60 stations whose measurements have just been tabulated is easily seen on plate 5. The accordance would be found to be just as good, however, if one selected at random any 60 of the 100 stations whose positions are shown by the dots. Detailed work on large-scale maps, the results of which have been published in other papers,[9] testify to the remarkably complete harmony between isobases and measurements.

In preparing the following summary of the attitude of this warped water-plane, such details as directions and rates of tilt have been worked

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[9] J. W. Goldthwait: Correlation of the raised beaches on the west side of Lake Michigan. Journal of Geology, vol. 14, 1906, pp. 411-424.

Abandoned shorelines of eastern Wisconsin. Bulletin of the Wisconsin Geological and Natural History Survey, no. 17, 1907.

A reconstruction of water-planes of the extinct glacial lakes in the Lake Michigan basin. Journal of Geology, vol. 16, 1908, pp. 459-476.

Preliminary report on measurements of altitude of the Algonquin and Nipissing shorelines in Ontario, July 6-August 11, 1908. Geological Survey of Canada. Summary Report of Director for 1908, pp. 112-114.

An instrumental survey of the shorelines of the extinct lakes Algonquin and Nipissing in southwestern Ontario. Geological Survey of Canada (in press).

out from maps whose scales range from 1:400,000 to 1:250,000. Plate 5, prepared from a much smaller map, is intended merely to show the broader features of warping, not to serve as a basis for estimating minute details.

Over the northern, or, more accurately, the northeastern, part of the Michigan-Huron basins the Algonquin beach has been upwarped so that it now slants southward at a rate that decreases down the slope of the plane. The inclination ranges from about 5 feet per mile in the north to 3 feet, 2 feet, 1 foot and less toward the south, to where the beach actually becomes horizontal, over the southern half of Lake Michigan.

The directions and rates of tilt in different districts, worked out after all available wye-level measurements had been plotted on large-scale maps, are tabulated in detail on page 235.

These figures have been tabulated again, in a more compact form, for the sake of comparison of tilt rates at corresponding altitudes in the different districts.

Tilt Rates of the Algonquin Beach arranged for Purposes of Comparison.

District.	Tilt rates, in feet per mile, between successive isobases.					
	0–50	50–100	100–150	150–200	200–250	250–300
Lake Michigan and Straits of Mackinac.............	1.16	1.82	2.85	3.33	3.40	....
West side of Lake Huron...	0.75	2.22	....	....	....	....
East side of Lake Huron and south side of Georgian Bay.....................	1.02	2.10	2.11	....	....	....
Lake Simcoe district.......	....	....	....	2.68	3.00	6 00
Average tilt rates	0.97	2.05	2.48	3 09	3 20	6.00

Not a small part of the discrepancies between tilt rates in the same vertical column in this table may be due to the necessity of taking stations which do not lie exactly on the isobases, and whose differences of altitude are consequently not 50 feet, but range from 32 feet to 71 feet. Detailed isobase maps drawn on a large scale show that the tilt rate is more uniform between isobases than one might at first suppose from the

Table showing the Tilt Rates of the Algonquin Beach.

District.	Between what isobases (approximately.)	From—	To—	Direction of tilt.	Descent (feet).	Distance (miles).	Tilt rate (feet per mile).
Over the Straits of Mackinac and the west side of Lake Michigan.	250 to 200	Hessel, 863 feet.	Mackinac I., 812 feet.	S. 15° W.	51	15	3.40
	200 to 150	Mackinac I., 812 feet.	Cross Village, 746 feet.	S. 15° W.	66	20	3.33
	150 to 100	Cross Village, 746 feet.	Harbor Springs, 709 feet.	S. 10° W.	37	17	2 85
	100 to 50	Harbor Springs, 709 feet.	Northport, 658 feet.	S. 9° W.	51	28	1.82
	50 to 0	Northport, 658 feet.	Herring Lake, 607 feet.	S. 5° W.	51	44	1.16
Over the west side of Lake Huron.	100 to 50	Alpena, 713 feet.	Greenbush, 642 feet.	S. 21° W.	71	32	2.22
	50 to 0	Greenbush, 642 feet.	Omer, 610 feet.	S. 21° W.	32	44	0.73
Over the south side of Georgian Bay and the east side of Lake Huron.	150 to 100	Owen Sound, 748 feet.	Port Elgin, 710 feet.	S. 21° W.	38	18	2.11
	100 to 50	Port Elgin, 710 feet.	Kincardine, 666 feet.	S. 21° W.	44	21	2.10
	50 to 0	Kincardine, 666 feet.	Grand Bend, 607 feet.	S. 21° W.	59	58	1.02
Over Lake Simcoe.	300 to 250	Kirkfield, 883 feet.	Orillia, 847 feet.	S. 21° W.	36	6	6.00
	250 to 200	Orillia, 847 feet.	Oro, 811 feet.	S. 21° W.	36	12	3.00
	200 to 150	Oro, 811 feet.	Holland Landing, 752 ft.	S. 21° W.	59	22	2.68

table. Plate 5, although a small-scale map, does not exaggerate the uniformity.

THE HORIZONTAL PORTION OF THE ALGONQUIN PLANE

Around the southern half of Lake Michigan, and near the south ends of Saginaw Bay and Lake Huron, the Algonquin beach is almost, if not quite, horizontal. The identity of the beach is somewhat obscured by the presence of another strong shoreline, the Nipissing, which stands only about 12 feet below the Algonquin in both basins and which replaces it for long distances where cliff recession has been rapid and long continued.[10] Moreover, cliff recession along the modern lake front has destroyed considerable stretches of both of these ancient strands. Nevertheless, the data collected seem complete enough to show that the Algonquin beach is virtually horizontal over this wide area.

The following table gives the altitudes of the Algonquin beach or its supposed equivalent at 19 localities in or near the region of horizontality. All the measurements except the one at Port Sanilac were made with the wye-level:

Altitudes of the Algonquin Beach in the Region of Horizontality.

Locality.	Altitude.	Authority.	Reference.
	Feet.		
Two Rivers, Wisconsin..	607	Goldthwait.	Bulletin Wisconsin Geological and Natural History Survey, No. 17, 1906, page 60, figure 11, and plate 12.
Evanston, Illinois.......	605	Goldthwait.	Bulletin Illinois Geological Survey, No. 7, 1908, pages 64–65.
Rogers Park, Illinois	604	Goldthwait.	Idem, page 66.
Holland, Michigan......	604	Taylor and Goldthwait.	U. S. Geological Survey.
Spring Lake, Michigan ..	603	Taylor and Goldthwait.	U. S. Geological Survey.
Muskegon, Michigan	604	Taylor and Goldthwait.	U. S. Geological Survey.
Arcadia, Michigan.......	603	Taylor and Goldthwait.	U. S. Geological Survey.
Herring Lake, Michigan.	607	Taylor and Goldthwait.	U. S. Geological Survey.
Frankfort, Michigan.....	605	Taylor and Goldthwait.	U. S. Geological Survey.
Worth, Michigan........	607	Taylor and Goldthwait.	U. S. Geological Survey.

[10] See Abandoned shorelines of eastern Wisconsin. Bulletin of the Wisconsin Geological and Natural History Survey, no. 17, 1906, pp. 44-45; and Reconstruction of water-planes of the extinct glacial lakes in the Lake Michigan basin. Journal of Geology, vol. 16, 1908, pp. 459-476. In the latter the altitude of the Algonquin beach was placed provisionally at 596 feet instead of 607 feet. The statement was made, ho ever, that this 596-foot beach might prove to be the Nipissing, and that the Algonquin might be expected at 607 feet (see p. 472).

Altitudes of the Algonquin Beach in the Region of Horizontality—Continued.

Locality.	Altitude.	Authority.	Reference.
	Feet.		
Bayport, Michigan......	607	Lane.	Michigan Geological Survey, Annual Report for 1900, volume 7, part 2, 1900, pages 47–51, and 75–76.
Sebewaing, Michigan...	{ 605 611 }	Lane.	Idem, pages 47 and 49.
Kawkawlin, Michigan...	610	Cooper.	Michigan Geological Survey, Annual Report for 1905, 1906, page 349.
Bridgeport, Michigan....	607	Cooper.	Tenth Annual Report, Michigan Academy of Science, 1908, pages 97–98.
St. Charles, Michigan....	607	Cooper.	Loc. cit.
Port Sanilac, Michigan...	605	Leverett and Taylor.	Information given by Mr. Leverett.
Sarnia, Ontario..........	605	Taylor and Goldthwait.	Canadian Geological Survey, Summary Report for 1908, 1909, pages 112–114.
Kettle Point, Ontario....	607	Taylor and Goldthwait.	Canadian Geological Survey, Summary Report for 1908, 1909, pages 112–114.
Grand Bend, Ontario....	607	Taylor and Goldthwait.	Canadian Geological Survey, Summary Report for 1908, 1909, pages 112–114.

Between the first two localities in this table there is a stretch of 150 miles in which no remnant of a beach at the 605-607-foot level has been discovered. The beach at Two Rivers is surely the Algonquin; the one at Evanston until recently was regarded as the shoreline of a local lake of the Michigan basin—Lake Chicago. The reasons for correlating it with the Algonquin are: (*a*) its strength; (*b*) its uniform altitude of 603-610 feet around the south end of Lake Michigan; (*c*) the horizontal attitude of the Glenwood and Calumet beaches of Lake Chicago, which stand above it; (*d*) the presence in it of molluscan shells, which are absent from the higher beaches; (*e*) the occurrence of forest beds beneath the beach gravels, believed to record the stage of low water during the earlier part of the activity of Algonquin River, and (*f*) evidences of erosion of cetrain valleys tributary to Lake Michigan to low levels, previous to the construction of this beach, as if to record the low-water stage just mentioned.[11]

[11] On these points see Leverett: The Illinois glacial lobe. Monograph of the U. S. Geological Survey, vol. 38, 1899, pp. 445-453.

W. C. Alden: Chicago Folio, No. 81, Geological Atlas of the United States, U. S. Geological Survey, 1902, pp. 10-11.

Goldthwait: Bulletin of the Wisconsin Geological and Natural History Survey, no. 17, 1906, pp. 109-111, 118; and Bulletin of the Illinois Geological Survey, no. 7, 1908, pp. 65-66.

For the Lake Michigan district these measurements give an average of 605 feet. Measurements with hand-level and aneroid barometer and contours of a large-scale map of the Sanitary District of Chicago agree in putting the height of the "Toleston," or "Algonquin," beach close to 600-605 feet around the south end of Lake Michigan. At the south ends of Saginaw Bay and Lake Huron the measurements average 607 feet. The altitudes at all 19 localities range from 603 to 610 feet. All of this variation of 7 feet can be accounted for by original differences in height of construction of the beach by the lake.

Even if we take the strong 596-foot (Nipissing) shoreline of the Lake Michigan basin as the equivalent of the 607-foot beach of the Lake Huron basin (although in the latter basin also is a strong shoreline at 596 feet, which seems surely to be the equivalent of the Nipissing beach of the Michigan basin), the extreme variation in height is between 593 feet and 610 feet, and of 40 wye-level measurements already recorded only one is below 595 feet. Thus for 350 miles from east to west and for 200 miles from north to south there is a variation of scarcely 17 feet in altitude, at most, of the Algonquin beach, and, if the distinction between the Algonquin and the Nipissing shorelines has been correctly made, of not more than 7 feet.

That the beaches around the head of Lake Michigan give little indication of differential uplift has long been recognized by those at work in the district, as reference to papers by Leverett, Alden, and others given above will show. The gathering of wye-level measurements has simply put the conclusion on a more satisfactory basis than heretofore, and has shown that the horizontal condition is more nearly absolute than might previously have been supposed.

The horizontality of the Algonquin plane is also wholly in harmony with the conclusions reached by Leverett and Taylor several years ago in the case of the beaches of lakes Maumee, Whittlesey, and Warren, around the south and west sides of Lake Erie. For Lake Maumee, Leverett states that

> "west of the Ohio-Pennsylvania line the slight variations displayed by each of its beaches are no greater than may be found along the present shore of Lake Erie; but near the Ohio-Pennsylvania line a differential uplift has caused the beaches to increase perceptibly in altitude in passing eastward." [12]

In the same region, the beach of Lake Whittlesey for a stretch of 200 miles varies less than 15 feet in altitude.

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[12] Leverett: Glacial formations and drainage features of the Erie and Ohio basins. Monograph of the U. S. Geological Survey, vol. 41, 1902, p. 739.

"A part of this difference [of altitude] may be due to discrepancies between the railroad surveys and a part to the difference in height to which the beach was built above mean lake level. These elements of error and of variation being eliminated, it is doubtful if enough difference will remain to require any crust warping." [13]

Similar statements are made by Leverett with regard to the beach of Lake Warren.[14]

The horizontality of the southern portion of a water-plane only 500 miles west of Lake Michigan was strongly suspected, indeed, as long ago as the '80's, when J. E. Todd and Warren Upham secured measurements of altitude of the beaches of glacial lakes Agassiz and Dakota. In his monograph on Lake Agassiz, Upham says, with reference to Todd's data:

"It is evident . . . that the long area of Lake Dakota has experienced only slight differential changes of level, at least in the direction from south to north since the departure of the ice. The James River Valley is thus strongly contrasted with the northern uplifting that has affected the Red River Valley, as shown by the beaches of Lake Agassiz." [15]

De Geer remarked, in 1892:

"As Prof. J. E. Todd and Mr. Upham have stated, the deserted shores of Lake Dakota, situated close to the southwest of Lake Agassiz, show no or only a slight unequal deformation. As the longer axis of this lake trends in nearly the same direction as the greatest warping of Lake Agassiz, it seems probable that the limit for this warping and at the same time for the upheaved area lies just between Lake Agassiz and Lake Dakota, or through Lake Traverse." [16]

THE "HINGE LINE" OR "ISOBASE OF ZERO"

The line which separates the region in which a beach has been upwarped from that in which it is still horizontal has been called by Leverett a "hinge line."[17] Because of its definite implication of warping on one side and stability or uniformity on the other, this term seems preferable to "isobase for zero," which was used by De Geer. The latter term, unless qualified by a more definite phrase, allows the interpretation that on one side of the line there has been differential uplift and on the other

[13] Idem, p. 756.
[14] Idem, p. 765.
[15] Upham: The glacial Lake Agassiz. Monograph of the U. S. Geological Survey, vol. 25, 1895, p. 267.
[16] De Geer: Proceedings of the Boston Society of Natural History, vol. 25, 1892, pp. 471-472.
[17] This term was suggested to Mr. Leverett by the facts in the Erie basin, but has not been used by him in print. It has been used by Coleman in a different sense, to mean a node line drawn from an extinct outlet through points where a beach splits vertically because of uplifts of that outlet. (See Coleman, Bulletin of the Geological Society of America, vol. 15, 1904, p. 363.)

side differential depression. It is interesting to see, however, that De Geer, in employing "isobase for zero," seems to have thought of it as a hinge line. In his remarks on the deformation of the shorelines of lakes Agassiz and Dakota, already quoted, he makes "isobase for zero" equivalent to "the limit for the uplifted region," and although he dwells upon the uplift north of the line, he says nothing to suggest depression south of it. The conception of a "hinge line" is, therefore, no new one.

Upham, De Geer, and others long ago recognized that successive uplifts probably did not hinge on the same line.[18] This appears to be true in a measure in the case of the upwarpings of water-planes of the Lake Michigan basin, for the northern limit of horizontality of the beaches of Lake Chicago is near the latitude of Milwaukee, Wisconsin, and Grand Haven, Michigan, while the corresponding limit for the Algonquin plane is about 100 miles farther north. Measurements of altitude of the plane of the later Nipissing shoreline, however, indicate that all post-Algonquin deformations hinged on a single line.[19]

THE ALGONQUIN PLANE AS A DATUM PLANE

It has been stated that south of the "hinge line" the Algonquin beach varies at most but 17 feet, and probably not more than 7 feet in altitude for 350 miles from east to west and 200 miles from north to south. Although this region may possibly have been raised or depressed from its original position so uniformly as not to warp the beach perceptibly, such a movement seems hardly probable. A variation of at least 20 or 30 feet might be looked for in such long distances. While recognizing the possibility of an even uplift or depression, therefore, we may reasonably favor the idea that in the region of horizontality the Algonquin beach stands today very nearly, if not precisely, where it stood when made.

Since the beach itself in this region has an average altitude of 605-607 feet above sealevel, the calm-water level of Lake Algonquin at this stage may be placed at 600 feet. This figure is open to certain corrections, however, for conditions peculiar to the latter part of the glacial period, chief among which is the lowered sealevel which resulted from the storing up of water in the ice-sheet.[20] According to Upham, the sealevel during the stage of greatest glaciation may have been 100 or 150 feet below its normal position.[21] By the time the ice-sheet had melted back

[18] See passages just referred to, and especially Upham, op. cit., p. 481.

[19] Goldthwait: Journal of Geology, vol. 16, 1908, pp. 473-474.

[20] R. S. Woodward: On the form and position of the sealevel. Bulletin of the U. S. Geological Survey, no. 78, 1888, p. 60.

[21] Upham: op. cit., pp. 515-516.

to the northern border of Lake Algonquin, however, a considerable portion of this water must have been restored to the sea. Hence the correction to be added to the 600-foot altitude of the Algonquin beach is probably much less than 100 feet.

This horizontal plane is a useful plane of reference from which to estimate the amount of post-Algonquin uplift of more northerly districts.[22] The figures 50, 100, 150, etcetera, on the isobases in plate 5 may, therefore, be conceived to indicate not simply the excess of uplift along those lines over uplift south of the "hinge line," but the total amount by which the altitudes of points on those lines have been increased since the time of the Algonquin beach.[23]

The Iroquois Water-plane

RELATIVE AGES OF THE IROQUOIS BEACH AND THE ALGONQUIN BEACH

The outline of Lake Iroquois in figures 1 and 2 is based on several maps, but especially those of Gilbert,[24] Fairchild,[25] and Coleman.[26] The location of the ice border, however, is wholly hypothetical, and shows only in a rough way the position of the Ontario ice-lobe as a barrier against the northwest side of the Adirondacks. The outlet into the Mohawk Valley at Rome, New York, is also shown.

It has long been thought that Lake Iroquois for at least a part of its existence was a contemporary of Lake Algonquin. The channel of the ancient Algonquin River, apparently connecting the two lakes, first suggested this relation.[27] More particularly, evidence seemed to have been found in a great delta built by the Algonquin River near Peterboro, Ontario, at about the level of the Iroquois Beach.[28] Gilbert, however, remarked that the correlation of this delta with the Iroquois beach was doubtful, and Coleman has more recently stated that the delta was built in a small tributary lake, which he names Lake Peterboro.[29] We can not

[22] The earliest printed statement of this idea is probably this sentence in fine print in Leverett's report on the surface geology of Alcona County, Michigan Geological Survey, Annual Report for 1901, p. 53: "The departure from horizontality here in Michigan may, therefore, be taken as a measure of the amount of uplift that has occurred."

[23] Goldthwait: The attitude of the Algonquin beach and its significance. (Abstract.) Science, new ser., vol. 28, 1908, pp. 382-383.

[24] G. K. Gilbert: The history of Niagara River. Sixth Annual Report of the Commissioners for the State Reservation at Niagara, 1890, pp. 61-84, map, pl. 5.

[25] H. L. Fairchild: Twentieth Annual Report of the New York State Geologist, 1902, pl. 19; and Bulletin of the New York State Museum, no. 127, 1909, pl. 42.

[26] A. F. Coleman: Bulletin of the Geological Society of America, vol. 15, 1904, pl. 22.

[27] Spencer: Proceedings of the American Association for the Advancement of Science, vol. 37, 1888, pp. 198-199.

[28] Gilbert: The Algonquin River. (Abstract.) American Geologist, vol. 18, 1896, p. 231.

[29] Coleman: op. cit., pp. 357-358.

conclude, therefore, that the Peterboro delta and the Iroquois beach are synchronous, and consequently that the Iroquois beach, the Algonquin River, and the Algonquin beach are synchronous. Indeed, Gilbert's observation that the channel of Algonquin River continues down the Trent Valley below the plane of the Iroquois beach to Lake Ontario may be quoted as evidence that Lake Iroquois had already disappeared before the Algonquin River ceased to drain Lake Algonquin;[30] in other words, that the Iroquois beach is of earlier date than the Algonquin beach. On figure 2 the Iroquois shoreline is drawn as a dotted line, because of this evidence that the two lake stages are not strictly synchronous.

The question, therefore, arises: "How much older is the Iroquois beach than the Algonquin beach?" Some light can be thrown on the question by examining and comparing the respective water-planes.

ISOBASES OF THE IROQUOIS PLANE

For plotting isobases of the Iroquois beach, measurements have been selected from those made by Gilbert,[31] Spencer,[32] Coleman,[33] and Fairchild.[34] Of these, Coleman's paper is of peculiar interest because his conclusions concerning the attitude of the Iroquois plane are matched very closely by those since reached for the Algonquin plane. The measurements are as follows:

	Feet	
Hamilton	363*	Spencer.
Waterdown	365*	Spencer.
Cooksville	400	Spencer.
Toronto Junction	422–425*	Coleman.
York	442*	Coleman.
Kingston Road	459*	Spencer.
Whitby	507*	Spencer.

[30] Gilbert: loc. cit.

[31] G. K. Gilbert: Old shoreline of Lake Ontario. (Abstract.) Science, vol. 6, 1885, p. 222.

Old shorelines in the Ontario basin. Proceedings of the Canadian Institute, 3d ser., vol. 6, 1888, pp. 2-4.

[32] J. W. Spencer: Deformation of the Iroquois beach and birth of Lake Ontario. American Journal of Science, 3d ser., vol. 40, 1890, pp. 443-451.

On the focus of regional post-glacial uplift. Transactions of the Royal Society of Canada, sec. 4, vol. 7, 1889, p. 129.

Evolution of the falls of Niagara. Geological Survey of Canada, 1907, pp. 203-204, 208, 277-284.

[33] A. F. Coleman: op. cit., especially pp. 358 and 359-362.

[34] H. L. Fairchild: Pleistocene geology of western New York; report of progress for 1900. Twentieth Annual Report of the New York State Geologist, 1902, pp. 103-139.

Gilbert Gulf (marine waters in the Ontario basin). Bulletin of the Geological Society of America, vol. 17, 1906, pp. 712-718.

Glacial waters in central New York. Bulletin of the New York State Museum, no. 127, 1909, pp. 54-55.

The measurements at Albion, Rochester, Auburn, Sodus, Rome, and Farrs were supplied by Professor Fairchild from his unpublished data.

	Feet	
Quays Siding	557	Coleman.
Colborne	602*	Spencer.
Trenton	632*	Coleman.
Queenstown	385*	Spencer.
Albion	430	Fairchild.
Rochester	440	Fairchild.
Sodus	456	Fairchild.
Auburn	411	Fairchild.
Canastota	441	Gilbert.
Rome	460	Fairchild.
Cleveland	484	Gilbert.
Constantia	489	Gilbert.
Richland	566	Fairchild.
Adams	640	Fairchild.
Adams Center	657	Gilbert.
Brookside Cemetery	700	Fairchild.
Farrs (east of Watertown)	733	Fairchild.

* These are wye-level measurements.

These measurements have been plotted at the respective localities on plate 5, and isobases have been drawn across Lake Ontario with reference to them. It will be noticed that the altitude of the Iroquois beach at York (442 feet) is nearly equal to that at Rochester (440 feet) and that at Canastota (441 feet). The isobase drawn nearly through these localities, therefore, serves to fix the probable direction of tilt at that altitude. It indicates what Fairchild and other writers have remarked, that the direction of tilt is more nearly due southward over the east end of Lake Ontario than over the west end. The same feature is met also in drawing isobases from Quays Siding (557 feet) to Richland (566 feet) and from Trenton (632 feet) to Adams (640 feet).

Coleman found that the direction of inclination of the Iroquois plane over the western part of Lake Ontario is about south 20 degrees west.[35] The isobases on plate 5 agree closely with his statement, running about 22 degrees south of east.

Comparison of the Two Water-planes

A comparison of the Iroquois isobases with the Algonquin isobases in southwestern Ontario brings out remarkable similarities of attitude in the two planes. The direction of tilt, as we have seen, is within one or two degrees of south 20 degrees west in both cases. This obviously means that the two beaches have been deformed by the same set of movements.

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[35] Coleman: op. cit., p. 360.

A still more remarkable resemblance between the Iroquois and Algonquin planes is found when the tilt rates of the two are compared. It is a matter of some convenience that the measurements available on the Iroquois beach are so distributed that they afford the construction of a set of isobases at 100-foot intervals, if we take for our zero the altitude of the beach at its southernmost point, Hamilton (363 feet). This has been done in figure 3. It is well recognized that the differential uplifts which warped the Iroquois plane extended southward as far at least as the head of that lake, at Hamilton, and an unknown distance beyond. Hence, although we take a line through Hamilton (in the direction 22 degrees south of east) as a zero line, we must not forget that zero is not a true measure of the amount of differential uplift at that place. It is quite probable that the post-Iroquois uplift at Hamilton amounts to 15 or 20 feet. We may therefore call the line a "zero plus" line, and the others "100 plus," "300 plus," etcetera. Having done this (see plate 5), we may examine the tilt rates between these isobases and compare them with the tilt rates between corresponding isobases of the Algonquin plane in the adjoining district.

Table for the Comparison of Tilt Rates of the Iroquois and Algonquin Planes

Portion of plane represented (isobases).	Iroquois plane.		Algonquin plane.	
	Data.	Tilt rate (feet per mile)	Data.	Tilt rate (feet per mile).
0 to 100	Hamilton (363 feet) to Kingston road (459 feet), 42 miles.	2.24	Grand Bend (607 feet) to Port Elgin (710 feet), 79 miles.	1.30
100 to 200	Kingston road (459 feet) to Quays (557 feet), 32 miles.	3.06	Port Elgin (710 feet) to Owen Sound (748 feet); and Holland Landing (752 feet) to Oro (811 feet), 40 miles.	2.43
200 to 275	Quays (557 feet) to Trenton (632 feet), 18 miles.	4.17	Oro (811 feet) to Kirkfield (883 feet), 18 miles.	4.00

The comparison shows in each case a somewhat steeper tilt for the Iroquis plane than for the Algonquin. This must be due in a measure to the fact that the zero isobase for the Algonquin plane marks the real limit of uplift, while the "zero plus" line for the Iroquois plane is probably a number of miles north of the true "hinge line." If we only know how far south of Hamilton to move the "zero plus" line to put it in the right position for a "hinge line," we might move the "100 plus," "200 plus," and "300 plus" lines southward to correspond, and we could then estimate the tilt rates more correctly. All these rates would, of course, be smaller after this correction than they appear in the table, because of the southward flattening of the plane; but the rate nearest the zero line would be affected most. The result of decreasing the tilt rates of the Iroquois plane in the table and of decreasing especially the rate of 2.24 feet per mile for the stretch between the 0 and 100 isobases, would be to make these tilt rates agree even more closely than before with the rates for corresponding stretches of the Algonquin plane.

The bearing of this similarity of attitude of the Iroquois and Algonquin water-planes upon the question of their relative ages is obvious. If, as Gilbert's observations seem to require, the Iroquois beach is older than the Algonquin, it can not be much older, for it has been tilted only a little more than the Algonquin. Uplifts are known to have been going on for some time previous to the two outlet stages of Lake Algonquin, and to have continued for some time after it. Yet the Iroquois beach seems scarcely to have been affected by those uplifts which preceded the two-outlet stage. The two beaches appear, therefore, to be almost synchronous. In other words, it appears that the Ontario ice-lobe had only recently withdrawn from the northwest slope of the Adirondacks when the Algonquin River ceased running and the Algonquin beach began to rise above the 600-foot plane.

The Isobases and the pre-Cambrian Boundary

In his paper on "Quaternary changes of level in Scandinavia,"[36] in 1891, De Geer said:

"The isanabases of Sweden were found to conform with the limits of the Scandinavian Azoic territory, and, according to the very latest determinations, not only in a general way, but also in many details. . . . The coincidence between the area of upheaval and the Azoic territory may possibly be explained by assuming that this territory, which is an old tract of erosion, has also been one of continental upheaval, which subsided during the ice age, for the greater part perhaps in consequence of the considerable ice-load, again rising after the release from the latter, though not to its former altitude."

Again, in his paper of the following year,[37] De Geer emphasized

"the coincidence of the uplifted area with the Scandinavian Azoic region, or what Suess has called 'the Baltic shield' . . . a well-defined tract where

[36] De Geer: Bulletin of the Geological Society of America, vol. 3, 1892, pp. 65-66.

[37] De Geer: On Pleistocene changes of level in eastern North America. Proceedings of the Boston Society of Natural History, vol. 25, 1892, pp. 454-477.

the old rocks are laid bare by erosion and the surrounding lands thickly covered with younger sediment. The limit of the Baltic shield, where it has been directly observed, and perhaps everywhere, is marked by great faults. Now the isobase for zero, or the boundary for the uplifted area, seems all the way a little outside of the above-named limit, and follows very conspicuously its convexities and concavities. Likewise all the other isobases point to a close connection between the upheaval and the geological . . . structure of the land."[38]

In the same paper, after reviewing the evidence then available for North America, De Geer writes:

"The conformity between ice load and subsidence seems to have been still greater here than in Scandinavia; and in this respect it will be very interesting to see what will result from a continued investigation of the warped beaches in the lake basin with its marked ice-lobes. . . . The connection between the subsidence and the geological structure of the earth's crust is perhaps not quite so striking as in Scandinavia. Still it seems probable that the Canadian Azoic or Archean region has changed its level more than the surrounding tracts. . . . The general conformity between the ice covering and the old Azoic plateäu makes it difficult, in the present state of our knowledge, in many cases to discern between the influence of these two circumstances." [39]

The question thus raised is too difficult to be answered satisfactorily even yet, because too little is known of the course of isobases outside of the Michigan-Huron-Ontario basins. An examination of the isobases for even this limited portion of the Great Lake region, however, is not without interest.

In the first place, the recent detailed studies of the Algonquin plane have indicated in every district that local irregularities, if present, are immeasurably small. The uplift around such depressions as Green Bay, Wisconsin; Grand Traverse Bay and Saginaw Bay, Michigan, and Georgian Bay, Ontario, show accordance—not discordance—with the broader, deeper lake basins adjoining them. The wye-level surveys have discovered no looping of the Algonquin isobases where they cross the lakes, such as one might expect from the greater thickness of the ice-lobes in those basins which are bordered by concentric moraines. If the melting away of the ice-sheet was the immediate cause of the uplifts of the region, the irregular load of these late, lobate stages must have been a very small factor in the equation, perhaps because the ice-sheet at that time possessed but a small fraction of its original thickness. The isobases run in a general way parallel to the boundary of maximum glaciation, but they

[38] De Geer: op. cit., pp. 458-459.
[39] Idem, pp. 473-474.

do not appear to conform at all to the more strongly lobate boundaries of later stages.

Comparing the Algonquin and Iroquois isobases with the pre-Cambrian boundary of Ontario (marked on plate 5 by a line of small crosses), we find a general parallelism. The pre-Cambrian boundary, to be sure, is much more irregular than the isobases; but some of its sinuosities may be ignored, since they indicate the presence merely of thin outliers of the sediments or of protruding inliers of the crystallines. The direction of the border of the crystallines seems not to depart for any considerable distance or to any considerable degree from the direction of the isobases.

Whether the Adirondack oldland in the east and the pre-Cambrian area of northern Wisconsin in the west were also central areas of uplift or not, around which the isobases of the Iroquois and Algonquin planes if extended would turn, is a question which can not be answered from data now at hand. Such measurements as are available give no indication of it.

In agreement with De Geer's statement, therefore, it may be said that the parallelism of isobases to the border of the pre-Cambrian oldland in Ontario is as suggestive as the parallelism of isobases to the border of the glaciated area; that a causal connection between the area of long-continued erosion, the area of glaciation, and the area of post-glacial uplift may fairly be inferred from the most recently collected facts.

Summary

Detailed surveys of the Algonquin beach around Lake Michigan, Lake Huron, and Georgian Bay have recently yielded a body of accurate data from which a set of isobases can be constructed on the upwarped plane of the Algonquin beach at intervals of 50 feet. Incidentally a datum plane appears to have been established, from which one can estimate the amount of uplift in more northerly parts of the Great Lakes region since Algonquin time.

Fewer measurements of altitude of the Iroquois beach around Lake Ontario furnish ground for the construction of a set of isobases at 100-foot intervals on the Iroquois plane.

The similarity between the two sets of isobases is remarkable, both as regards the direction and the amount of tilt indicated for corresponding parts of the planes. Accepting Gilbert's conclusion from physiographic evidence that the Iroquois beach is of earlier date than the Algonquin, we are led by this comparison of the two tilted planes to conclude that the difference in age between them is probably very slight.

The rough parallelism of the isobases with the glacial boundary on the one hand, and with the border of the pre-Cambrian oldland of Canada on the other, in connection with the marked increase of tilt rate near the latter boundary, seems to strengthen the position taken by De Geer[40] twenty years ago, that in North America, as in Scandinavia, the central areas of the recent upwarpings were not merely centers of glaciation, but centers of continental uplifts of much earlier dates.

[40] In his view regarding the central area of uplift in Canada, De Geer followed Spencer, who as early as 1889 attempted to locate the precise center of post-Algonquin upwarpings in a paper "On the focus of regional post-Glacial uplift" (Transactions of the Royal Society of Canada, section 4, vol. 7, 1889, p. 129). Spencer reached the conclusion that the center or focus was on the height of land southeast of James' Bay. De Geer's isobases are concentric with that point. In view of the subsequent discovery of the far westward trend of the isobases of Lake Algonquin and Lake Agassiz, it now appears that if the uplifts centered around any one point, that point was much farther north than Doctor Spencer supposed, or that the uplifts centered along an axis which trends westward from his "focus."

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CACOPS, DESMOSPONDYLUS; NEW GENERA OF PERMIAN VERTEBRATES[1]

BY S. W. WILLISTON

(Presented in abstract before the Paleontological Society Dec. 30, 1909)

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[1] Manuscript received by the Secretary of the Geological Society April 23, 1910.

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Introduction

CHARACTER OF THE PERMIAN BEDS OF NORTHERN TEXAS

In a field experience dating from July, 1874, in nearly every known vertebrate horizon of North America, I know of no beds so difficult of exploitation as those of the Permian of northern Texas. As a rule the vertebrate fossils are found more or less broken and weathered, scattered about on the sloping exposed surfaces. Occurring as the bones do, almost invariably concealed beneath a thin or thick covering of cemented matrix, so like the color and form of the countless millions of nodules, it is only when they have been broken up and weathered by exposure that the slight colorational differences presented by the fractured surfaces distinguish them. It thus happens that by far the larger part of the material secured, especially that of the smaller animals, is more or less fragmentary in character, though fortunately preserved from rapid disintegration by the covering of more or less intractable matrix.

CONDITIONS OF FOSSILIZATION

The middle portion of the deposits is to a large extent free from nodular concretions, presenting smooth, clean surfaces of red clay, especially inviting to the collector. But, unfortunately, it is these attractive deposits which are the most barren of fossils. I have searched patiently over such beds for many successive hours without being rewarded by a single fragment of a fossil; and it is for this reason that one, after a little experience, learns to avoid these clay deposits, or gives them but scant attention. Nevertheless it is in these "barren" deposits that the prizes of the Texas Permian are to be sought. When fossils do occur in them, they usually are excellently preserved and largely free from the exasperating matrix. Professor Case has observed that but one or two specimens may be expected from these clay beds in a season's work, and he is not far wrong in his estimate. And it was one of these prizes which was discovered by Mr. Paul Miller, of the University of Chicago Expedition of 1909, between the valley of Indian Creek and the Wichita River, about 5 miles west of the Vernon road. A large quantity of small bones weathered out and lying in a small gully led to the detection of a bone bed or "quarry" that is without equal in the history of the Texas Permian exploration. The clay lying over the mass of bones protruding from the hillside was entirely free from nodular masses, and, with the exception of a few ounces of bone fragments a half mile away, not another indication of a fossil was discovered in the adjacent exposures covering several hundred acres. The clay was excavated down to the level of the bones, and the bones were then removed in large clay blocks securely bandaged. It was found quite inexpedient to attempt the removal of the bones from the matrix in the field. Not only was the thin adherent matrical covering of the bones so perfectly like the clay in appearance that to distinguish the bones from fragments of the indurated clay when loosened required the most minute examination, but the interlacing of the numerous skeletons in the mass prohibited the attempt to separate them in the field. Indeed, in the laboratory the only safe way to prevent the loss of small bones and fragments of bones when dissociated is to dissolve the clay in water. As it was, with the inadequate tools at our command near the close of the season, the complete excavation of the bed was not attempted, but will be resumed the present season by Mr. Miller, when it is confidently expected that much additional material will be secured.

The skeletons lay in a narrow deposit about 5 feet in width and of unknown extent throughout a thickness of about 2 feet, and apparently on a sloping horizon. They are almost invariably found lying on the ventral side, and for the most part with the members undisturbed, save that in some cases the phalanges of the feet are more or less scattered about, and the tail or whole limbs may be dislodged. Many of the bones have a very thin layer of cemented clay covering them; others are more or less cemented together in nodular masses. It is very evident from the character of the deposits and the position of the bones that the skeletons had suffered but little disturbance after death; that the creatures had for the most part died peacefully in a stagnant, perennial pool of water, successive generations piled upon each other in layers.

I estimate that, so far, there is evidence of at least 50 or 60 skeletons in the deposit. From the loose material recovered from the surface I count over 50 femora, nearly as many humeri and corresponding girdles, with large quantities of the vertebræ. In the blocks containing the thickly aggregated skeletons secured, there are probably representatives of at least as many more, judging by the two or three blocks that have been so far worked out. How many more remain to be secured the present season I can not even conjecture. We anticipate as much more material as we already have.

ASSOCIATED VERTEBRATES

Not many different kinds of animals are represented by the remains so far examined. The great majority of the skeletons belong to the genus *Varanosaurus* Broili. Another genus of reptiles, very clearly new to science and of about the same size as *Varanosaurus*—that is, 4 feet in length—is represented by fewer remains, but still sufficient, it is confidently believed, to furnish the complete structure of the creature. So far, of this form, the complete hind legs and feet, pelvic girdle, and tail have been worked out, and two skeletons are running into the block matrices. Its restoration and description will be published as soon as possible. A third genus of reptiles, also new to science, represented so far by a femur, which is described and figured (plate 16, figure 5) in the present paper as *Desmospondylus,* was also found. All the amphibian remains so far obtained belong to the present genus *Cacops,* and consist of the nearly complete skeleton shown in the restoration in plate 17, together with another skeleton less complete, portions of two other skeletons and skulls, and various remains of less moment found in the topmost layers. I doubt not that the present material on hand will disclose additional skeletons of this genus more or less complete. One skeleton of *Varanosaurus*, complete from the tip of the tail to the back of the skull, has been completely worked out and figured in 20 plates. An additional skull of another skeleton still leaves some details to be determined, doubtless to be found in other skeletons and skulls yet in the matrix. The full description, with figures and plates of the skeleton of this form, will follow the present paper within a year.

The skeleton of *Cacops,* as shown in plate 17, is composed exclusively of one specimen, with no more plaster in its construction than was necessary to cement the freshly broken parts in its preparation, save of many of the phalanges, as is described further on. The specimen was not only prepared by Mr. Miller, but was skilfully mounted by him in the course of a couple of months' labor. It is doubtful whether another type of fossil vertebrate animal of the size of this is represented by as complete material as is *Cacops aspidephorus*.

Cacops aspidephorus—Genus and Species new

SKULL

(Plates 6, 7, 8)

Two skulls, nearly complete, and portions of two others have so far been recovered from the matrix. Of these the one in the mounted skeleton was quite complete, but suffered slightly at the front extremity in its collection. The best specimen, however, the one from which the following description has been drawn, was a skull quite complete, attached to another skeleton, from which the posterior end of the mandibles only was lost in collecting. This skull is slightly smaller than the mounted one and had suffered very little distortion. It has been freed from every particle of matrix, even that of the brain and nasal cavities. Unfortunately, in none of the specimens has it been possible to determine the sutures, in part because of the complete ossification of the bones; in part, perhaps, because the removal of the thin investing matrix has obliterated whatever indications of them might have been present. The dermal surface is everywhere rugose, with small, irregular pits and ridges.

The skull is broad and depressed, broadest opposite the posterior part of the orbits, with a gentle, perhaps somewhat irregular, convexity on the sides. The epiotics project backward strongly, leaving a deep concavity in the middle behind. The nares are large, oval in outline, directed upward, forward, and outward, broadly separated in the middle, and approaching closely the margin of the maxillæ. The orbits are large, subcircular in outline, the opening looking obliquely upward. Near the middle of their front margin the border is angularly thickened, descending in a steep declivity outwardly. In the middle posteriorly, also, there is a similar, but more angular, thickening, which extends back as a ridge to form the lateral margin of the cranial table, overhanging the otic cavity posteriorly. Almost continuous with the upper orbital margin, there is another elevated ridge running backward and outward to join the lateral border over the middle of the otic cavity. Between these two ridges there is a triangular space of considerable size, more or less depressed in its middle. The least distance between the orbits, near their middle, is but little or no more than one-half the lateral diameter of the orbit. The large parietal opening is located about one-third of the distance between the hind borders of the orbits and the occipital margin in the middle. Just in front of the concave hind border of the table the margin is elevated into a prominent rugose crest or ridge, highest in the middle, possibly for the attachment of nuchal muscles. The cranial table in front of this transverse rugosity, and between the slightly elevated lateral margins, is flat or gently concave.

On the sides posteriorly there is a large cavity, with an angulated slit-like opening at its bottom, forming a false temporal fenestra, which doubtless is merely a greatly enlarged and closed otic notch.[2] It is bounded above by the heavy overhanging lateral border of the cranial table. The epiotic angles, produced into long horns, instead of ending freely, as in other Stegocephala, turn directly downward to fuse with the quadrate below, inclosing what would otherwise be a simple notch into a large fossa and opening. Its whole exterior and outer surface is roughened like other parts of the skull. The cavity thus inclosed extends angularly at its upper anterior angle to within about 20 millimeters of the middle of the hind border of the orbit and is smooth throughout. At its bottom there is a thin, flat, angular plate, attached to the lower anterior inner side of each epiotic horn, projecting upward and forward to an acute angle, leaving a narrow, slitlike perforation above connected with another in front reaching the lower part of the cavity, angularly dilated at the upper anterior part. Close to the anterior border of this plate, and near its upper angle, is the projecting end of the stapes, as shown in plate 8, figure 1. The upper margin of the perforation in front is formed by a narrow descending plate from the rugose upper border of the cavity. The front wall of the cavity slopes backward from the upper angle to a little above the quadrate articular surface; its smooth wall looks obliquely upward, backward, and outward. It seems probable that this cavity, as thus bounded, was closed by a tympanic membrane, against which the continuation of the stapes abutted.

The precise limits of the epiotic process are not certain, but a distinct line is evident on one side, indicating sutural attachment with the quadrate along the posterior side of the platelike expansion and to within a short distance of the articular projection. This, I am aware, is an unusual position for the quadrate, with the ear-slit or opening above and in front of it, but there can be no other interpretation of the structure. The quadrate is well ossified below, fused with the extremity of the pterygoid on the inner side and with the quadrato-jugal in front below.

The occipital surface of the skull has, in the middle, a smooth, steep declivity, with the small foramen magnum at the bottom, not more than 5 millimeters in diameter. The high rugosity of the posterior border of the cranial table overhangs slightly this declivity, forming a fossa into which doubtless were inserted the strong neck muscles. Just outside of

[2] A closed otic notch is not unknown among Stegocephala. See Woodward, Proceedings of the Zoological Society, 1904, p. 170, plate xi. *Capitosaurus stantonensis* Wood.

each condyle there are the usual two cranial foramina at the base of the paroccipital processes, which extend outward, joining the epiotic on the under side and turning downward to terminate at or near the upper posterior corner of the quadrate. Between this paroccipital process and the roof, at each side, there is a moderately large post-temporal vacuity leading into a deep cavity just inside the "tympanic" rim of the ear cavity and below the roof of the skull.

The structure of the under side of the skull, while not departing far from the usual stegocephalan type, is somewhat remarkable. The palatal cavity as a whole had a high arched roof, with a slender, almost vestigial, parasphenoid dividing the large pterygoidal vacuities so characteristic of the amphibia. The internal nares are larger than the external ones, situated either side close to the teeth, with their front margin almost below the hind margin of the external nares. On the inner side of each there is a stout, conical, recurved tooth, about 10 or 12 millimeters in length, and another like it is situated near the posterior margin of the orifice, not far from the maxillary teeth. These are the only teeth located on the palatal surface. The palatines, or conjoined palatines and pterygoids, on each side posteriorly and internally to the nares slope strongly upward. In the middle in front the vomers or anterior end of the parasphenoid is about 15 millimeters in width where it joins the palatine shelf, narrowing to about 4 where it joins the rhinencephalic chamber. Posteriorly the arrangement of the basicranial bones is very similar to that of *Trematops* or *Eryops.* The ossified basisphenoid sends downward and outward a stout basipterygoid process to join the pterygoids on each side, the juncture indicated by a thickening as in *Trematops.* Outwardly the pterygoids form a vertical plate, probably with the conjoined epipterygoids, reaching to the cranial wall, save for a small vacuity near the roof, leading into the deep temporal cavity under the roof, into which the post-temporal vacuity also opens, a cavity open below back of the pterygoids between the basicranial bones and the posterior wings of the pterygoids. In the middle the parasphenoid continues forward from the basisphenoid as a slender rodlike bone nearly to the flat anterior end. For a short distance it forms a high bridge, above which in front is the inferior opening of the parietal foramen. For the larger part of its distance, however, it is closely united as a thick ridge to the lower side of the elongated rhinencephalic chamber (see plate 7 and plate 8, figure 1). Between this chamber and the closed brain-chamber behind there is a large orifice on each side for the escape of the optic nerves. This elongated arched chamber has its anterior borders also free and curved a little back of the anterior margin of the orbits. In front of this the roof of the skull has been somewhat pressed down upon the palatal bones, but there was evidently in life a high cavity for the nasal region, in which are various indeterminate bone remains, doubtless the ethmoidal and turbinate. A little in front of the basisphenoid the pterygoids give off a rounded or subangular process much as in the allied forms, narrowing the opening of the infratemporal fossa, which is broad and deep behind, where its thin upper posterior roof forms the anterior inferior wall of the otic cavity.

The basisphenoid is concave in the middle; on either side it has a flattened basisphenoid process, as in *Trematops,* directed downward and backward, underarching a rather deep fossa. Opposite these on either side is the root or base of the pointed, stylelike stapes, which is directed outward and backward to terminate, as already described, at the upper angle of the quadrate, in the auditory vacuities. Whether or not it has a foramen at its base I can not say. Above and in front of this, turned upward to reach nearly to the inner surface of the superior tympanic ridge, is the proötic bone.

A comparison of the structure of the basicranial region with that of *Trematops* shows great similarity, quite confirming my suggestion that the pseudotemporal vacuity is in reality merely the closed otic notch for the opening of the external ear. The opening in *Trematops,* however, is far smaller than in *Cacops,* and extends somewhat further forward toward the orbit. The small size of the parasphenoid in the present genus also explains its apparently entire absence in *Trematops,* though it is not improbable that the rhinencephalic canal in *Trematops,* were it preserved complete in the type specimen, would show the remains of the parasphenoid coalesced with it as in *Cacops.*

The maxillary teeth in *Cacops* are all small and of nearly uniform size, in an uniform closed series. I count about 20, but it is possible there may have been a few more.

The mandible is remarkable for its slenderness. Posteriorly it has a broad expansion, but the ramus from the middle of the orbits forward is slender. A deep fossa is present in front of the condyle, and the median symphysis in front is a little expanded. It has apparently the same number of teeth as in the maxillæ, and all, like them, are of uniform size.

VERTEBRÆ

(Plate 9)

The vertebral column of the mounted skeleton was apparently quite complete as it lay in the matrix in association with skull and limbs. In the removal of the thin incrusting matrix, however, a few of the pleurocentra of the anterior vertebræ and some of the small elements of the tail were lost, notwithstanding the most scrupulous care. Of these, only the possible pleurocentra of the atlas and the dorsal elements of the first 5 or 6 caudal vertebræ have any morphological significance; future preparations of other skeletons yet contained in the matrix will doubtless complete even these small details. The column as found was continuous from the skull to the tip of the tail, without break, save that the last few caudal vertebræ were slightly angulated from the rest of the series. The presacral vertebræ had a gentle, sinuous curve, with the convexity to the right as far back as the end of the dermal carapace, to the left from thence to the sacrum. There is also a slight vertical sinuosity in the same regions, convex above anteriorly, below posteriorly. These curvatures seemed so normal that no attempt has been made to reduce them in the mounted skeleton, and I have figured the column as it lay. A slight pressure to the left has crowded the ribs upward on that side and downward on the opposite side, but to a very slight extent only. The perfect union of the different elements, at least as far as the beginning of the chevron caudal vertebræ, removes all possible doubt as to their number and relations—21 presacral, 2 sacral, 6 pygals, and 15 or 16 chevron caudals. The spines, save those of the first 2 vertebræ, are of nearly uniform length throughout the carapacial series, 15 in number, a trifle longer perhaps in the anterior and middle region, and a little more slender in the last 3 or 4. Those of the free presacral vertebræ are progressively shorter and less stout. Throughout the series covered by the carapace they are slightly thickened at the upper end, with the anterior and posterior margins thinned, and with a lateral ribbed thickening on each side near the middle, as though for the support of the terminal expansion. Covering the top of each spine there is a rooflike expansion, wider in the middle and narrowed at each lateral end. Their sides slope downward at an angle of about 45 degrees to the full width of the superincumbent dermal scutes. The anterior margin of these plates is uniformly beveled for articulation with the posterior margin of the superincumbent intercalated dermal scute. The posterior beveling is much broader in the middle. Presumably these expansions are outgrowths from the top of the spine, cartilaginous in origin, but of this I do not feel entirely assured, since in every case where I have removed them I have found what appears to be a sutural surface, and the top of the spines is rounded on the margin, with an extrant angle between it and the plate. The surface of these expansions is smooth, both above and below. The narrowed outer extremities are either rounded or with a slight emargination. The first of these expansions, that of the second vertebra, is small, subtriangular in shape, with rounded corners, and appears not to have been covered by a dermal scute. The second expansion is larger, becoming broader behind, and is covered, on its posterior part only, by the first dermal scute. The posterior end of the carapacial series tapers more gradually than does the anterior to a narrower extremity, and like that has, apparently, no dermal plate over the last of the series, the penultimate spinal expansion supporting the posterior margin of the last dermal shield. Throughout this series the thinned expansions of the spines above, anteriorly and posteriorly, touch each other in the present curved condition of the column. In the most anterior part of the column, however, the hypocentra are slightly separated, with one longer interval, producing a slight convexity of the series below. It thus seems certain that the position in which the column was found, and which has been retained in the mounted specimen, was a normal one for the living animal; that is, with a gentle convexity antero-posteriorly of the carapace, and a slight concavity below. Nor would it have been possible for the living animal to have fully straightened out the column without actually dislocating the zygapophysial articulations. A slight lateral bending was possible in life, as shown by the position in which the bones were found; but even this could not have been extensive in the front part, since the free dermal plates which glided smoothly over the fixed spinous expansions would have met each other at their lateral extremities, if the curvature was at all decided. Back of the carapace, however, a greater flexibility was possible, since the zygapophyses here are somewhat larger, and the free spines were separated above by a greater interval.

CARAPACE

(Plate 9 and plate 12, figures 5, 6)

The dermal plates are of nearly uniform length, increasing slightly in expanse to the middle of the series—that is, at the summit of the dorsal convexity. Each fits accurately and closely over the contiguous borders of the adjacent spine roofs, separated from each other by a space of 1 or 2 millimeters. It is evident, from the structure of the spine expansions with the greater beveling in the middle behind, that the chief motion was at the anterior part of each dermal plate. The upper surface of these plates is slightly irregular, with shallow depressions or pits, the margins in front and behind parallel, with a slight obliquity backward; their outer angles are slightly rounded, and their outer, thin borders are nearly straight, or with a slight emargination. Each of these dermal plates is composed of two elements, a median longitudinal suture being evident in many of the shields. In the middle of each above there is a shallow groove bordered on each side by a slight elevation.

In the structure of the dorsal shield or carapace the genus is identical with *Dissorophus,* save that the carapace of the latter genus is very much more extensive, covering practically the whole of the dorsal side of the animal and probably extending further back. Furthermore, in *Dissorophus* the anterior shield is very large, covering several vertebræ, very much like the anterior shield in certain armadillos. That these differences in the carapace, together with others of the skeleton, as shown in an excellent specimen of *Dissorophus* in the University of Chicago collections, which will be fully figured later, are not due to age, is evident from the close correspondence in all skeletal characters between several specimens found associated in the present matrix. These differences will be summarized in the taxonomic discussion on a later page.

CARAPACE IN ALLIED FORMS

Most remarkably similar are the dorsal shields of the genus *Aspidosaurus* Broili, which in other respects, so far as the skeletal characters are known in the rather fragmentary type, resembles so closely the present form that I was for a long time almost assured of their identity, and this opinion was also shared by Doctor Broili, to whom I sent for comparison photographs of the drawings of the plates illustrating the present paper. But a careful study, not only of the figures and descriptions given by Broili, but also of a fragmentary specimen in our present collections, which must be identified as conspecific with the genotype of *Aspidosaurus,* quite convinces me, as it has also Doctor Broili, of the generic distinction between the two forms.

In *Aspidosaurus* there is but a single dermal expansion over each spine, apparently coössified or continuous with the top of the spine, which overlaps the preceding one like shingles on a roof. Or, as Broili has stated it:

> "Diese Hautverknöckerungen treten nun in innige gegenseitige Verbindungen insofern sich dieselben aufeinanderliegen und zwar immer die folgenden auf die vorausgehende Ossification, wodurch das Gänze gewisse Aehnlichkeit mit dem First eines Hauses gewinnt. Diese eigenthümliche Schutzapparat fällt noch besonders durch seine Skulptur auf, welche die nämliche kräftige Ausbildung zeigt, knötchenartige durch Leistchen verbundene Auschwellungen, wie der Schädel. Die Unterseiten dieser Hautverknöckerungen sind glatt, nur ihrer seitlichen Ränder weisen leichte Einkerbungen auf."[a]

Of the specimen above mentioned I give figures (plate 10, figures 2, *a*, *b*) showing this very characteristic difference. It is seen that the broad

[a] Paleontographica, vol. li, 1904, p. 42.

spinous expansions overlap like shingles the ones preceding. The roof also differs in the greater angularity of the ridge, the sides sloping at a greater angle, while in *Cacops* there is a median depression or shallow groove, and the lateral plates are more convex. The spines supporting these plates are much more expanded above than is the case in *Cacops*. From Broili's figure of the type of *Aspidosaurus* it is not certain that the otic notch is inclosed by bone, as in the Dissorophidæ, though the emargination shown would suggest that such may be the case.

A specimen recently described by Case[4] and referred doubtfully to *Zatrachys apicalis* is in all probability a species of *Aspidosaurus*, a genus apparently overlooked by the author. The author described the carapace as having overlapping plates, with great angularity, apparently quite as in the specimen herewith figured, and as in the type specimen figured by Broili. If the specimen be conspecific, or at least congeneric with *Aspidosaurus*, as I doubt not, then an additional generic character is furnished by the ribs. These have an elongate hooklike process directed upward and backward over the succeeding ribs, quite unlike the structure in *Cacops*.

Altogether the differences presented by *Aspidosaurus* are so fundamental that I believe Broili was justified in separating the genus from *Dissorophus* on the character of the carapace alone. If so, then certainly *Cacops* can not be united with *Aspidosaurus*, even though the size and extent of the carapacial development is much more like that of this genus than of *Dissorophus*. Possibly the *Aspidosaurus* type of roof has been derived from that characteristic of the Dissorophidæ by the anchylosis of the dermal scutes with the superior expansions of the spines, but even such a difference as this is of generic importance.

Other genera of temnospondyles are known to possess similar carapacial developments. *Euchirosaurus*, from the Lower Permian of France, has a broad dilatation of the spines above, though not platelike. Very similarly expanded spines I have seen in specimens from the Texas Permian, but have been inclined to refer them to the basal caudal region of *Eryops*.

The structure of the dorsal expansion of *Zatrachys* is very imperfectly known, unless, indeed, Case was right in referring his species *apicalis* to that genus. The vertebræ are unknown in the type species. In another species, referred to the genus by Cope later, the real *Z. apicalis*, he described the spines as follows: "The summits of the neural spines are expanded and the superior faces of the expansion are tubercular and have

[4] Bulletin of the American Museum of Natural History, vol. xxiii, 1907, p. 665.

a median prominence. The expansions are sometimes large, resembling the dermal bones of the crocodiles, and in that case the median prominence is a keel. On the smaller expansions the latter is a mere apex. There are narrow, flat bones which I suppose to be neural spines, which are ornamented with innosculating ridges."[5] These characters agree better with a spine figured and described by Case as *Zatrachys crucifer* Case,[6] the type of which I have examined. This is of much larger size, and is in the shape of a cross, the median projecting piece above and the upper surface of the transverse arms are deeply pitted—a radically different type from that of either *Aspidosaurus* or *Cacops.* The description of the skull seems to preclude the possibility of the genotype being congeneric with *Cacops aspidephorus.*

HYPOCENTRA

(Plate 9, plate 12, figure 7, and plate 14, figure 12)

The hypocentra, like the arches, are of nearly equal size and extent throughout, rather strongly and smoothly convex from side to side, gently concave antero-posteriorly. The second to the eighth back of the atlas have, on each side, near the upper angle posteriorly, a facet or protuberance for the capitular articulation of the rib. The first hypocentrum back of the atlas is smaller than the succeeding ones; it is shorter and has more acute lateral margins, and is, apparently, without facets for the capitular articulations. The second hypocentrum is also somewhat smaller than the succeeding ones, but is provided with a parapophysial protuberance on each side.

PLEUROCENTRA

(Plate 9 and plate 12, figure 5)

Of the first four vertebræ back of the atlas the pleurocentra were not recovered; they doubtless had dropped out of their places and were not recognized in the matrix, since a slight depression of this part of the column had loosened all the elements somewhat. However, in the connected series places for them are shown with articulations indicating but little variation in size from that of the following ones. In size the pleurocentra of the remaining vertebræ are nearly uniform, perhaps slightly longer anteriorly than posteriorly. Each articulates broadly with the posterior side of the pedicel of the neurocentrum, and, less extensively, with the anterior side of the following neurocentrum, as shown in plate

[5] Proceedings of the American Philosophical Society, vol. xvii, 1881, p. 523.
[6] Journal of Geology, vol. xi, p. 399.

12, figure 5, and by the narrowed lower extremity with the posterior superior margin of the hypocentrum, fitting into the angular space between the adjacent neurocentra. The large flat sutural surface for union with the preceding neurocentrum indicates a close, firm union, while that with the succeeding neurocentrum and hypocentrum is more rounded. The pleurocentrum of the first presacral vertebra is narrower than the preceding one. The pleurocentra of the two sides of each vertebra are closely approximated in the middle above a small concavity on the upper side of the hypocentrum, leaving in the articulated parts a persistent notochordal canal.

The zygapophyses are stouter in the free or lumbar portion of the column than in that part covered by the carapace, as would be expected, since the comparative rigidity of this part prevents extensive motion of the individual vertebræ upon each other. Their articular surfaces look uniformly upward and inward, and downward and outward, at an angle of something less than 45 degrees.

The diapophyses arising from the neurocentra increase rapidly in vertical extent of their rib attachment as far as the eighth, the border continuous with the parapophysial projection on the hypocentra. The ninth suddenly decreases in width, with a wide interval between its lower end and the hypocentrum, which has no parapophysial facet. From the ninth the transverse processes are narrower, with the extremity for rib articulation of but moderate extent. Throughout the series the processes are directed almost transversely outward, with the upper nearly horizontal margin a little thickened and rounded; the upper margin arises a little below the zygapophyses anteriorly, a little lower down posteriorly. The rib margin is straight or gently sinuous from above downward, thinned below and slightly emarginated, ending, as has been described in the first eight, in apposition with the parapophysial facet on the hypocentra. The lower end of the rib margin is considerably in advance of the upper. Beginning with the ninth, where the ribs become single-headed, the transverse processes are of nearly uniform width, the articular surface for the rib placed obliquely to the vertical line. Beginning with the seventeenth vertebra, the first behind the carapace, the diapophyses shorten rapidly, becoming almost sessile in the last two, in which the rudimentary ribs seem to be anchylosed to their extremities.

ATLAS

The atlas was preserved in this specimen in place. It is somewhat eroded and does not seem to differ from a better preserved specimen belonging to the closely related genus *Dissorophus*, which I have figured in plate 14, figure 11. This vertebra seems to be a single element, though doubtless it is composed of coalesced hypocentrum and neurocentra; but I can distinguish no sutural lines. The anterior surface shows two facets for articulation with the occipital condyles. On the posterior side the body has a deep concavity, pierced above its middle by a small notochordal foramen. The neuropophyses are simple processes, of nearly uniform width, and flattened; they lie closely in apposition with the sides of the spine of the second vertebra. The same condition is found in *Eryops* and *Trematops*, and is doubtless the usual structure of the atlas in the rhachitomous amphibians. Back of the neurocentra I find no articular surface for the attachment of pleurocentra, though the anterior border of the next vertebra seems to indicate the presence of small pleurocentra.

The real composition of the atlas of the rhachitomous amphibians—for I doubt not that the vertebra is homologous with the atlas of the higher vertebrates—is a matter of some importance. If there be pleurocentra between the atlas and second vertebra, then we have the same structure as exists in the reptiles and higher vertebrates, the atlas composed of hypocentrum and neurocentra, the pleurocentra separated to unite with the axis. Against this interpretation, however, is the fact, as seen in the drawings, that the notochordal opening pierces the centrum precisely as it does in the later vertebræ—that is, between the pleurocentra and hypocentrum. If all three elements are coössified in the atlas, then it would lend support to the views held by some morphologists, of whom Broili has given the latest exposition, that the vertebræ of the amniota are composed of the combined hypocentrum, pleurocentra, and neurocentra.

The second vertebra of the series, which we may call the axis, because of its slight modifications in structure, has a smaller hypocentrum, as I have described, without parapophysial facets. The diapophyses are short and narrow at their extremity. The spine is much broader below than are the succeeding ones and pointed above, where it comes in contact at its extreme tip with the extreme front end of the carapace. On either side of the thinned anterior expansion of the spine below there is a slight depression, in which is lodged the slender flattened neuropophysis of the atlas.

SACRUM

(Plate 9)

As is well known, the reptiles and higher vertebrates, wherever they possess a sacrum, have invariably, or almost invariably, two or more vertebræ composing it. And this is one of the characters which have been urged as indications of direct genetic relationship between the microsaurs, in which two sacral vertebræ are known to occur in some forms at least, and the reptiles. Hitherto, not only among recent, but also among extinct, amphibians, excluding the Microsauria, but one sacral vertebra has been known to occur, though I find certain references to sacra with two vertebræ among the older writers on the stegocephs. In *Cacops* we have two well developed pairs of sacral ribs broadly attached to the ilia. Of these, the first pair is a little larger and stouter than the second, though differing otherwise but slightly. The stout vertebral ends have two articulations, with a small non-articular surface between them, the upper and larger one attached firmly to the neurocentrum, the lower to the upper border of the hypocentrum, which again presents a parapophysial protuberance for its union. The somewhat crushed condition of the arches of the sacral vertebræ, as they were found lying in the pelvis, prevents the determination with certainty of the relations of the neurocentra to the hypocentra, but I suspect that they articulate on the sides with the ribs only and not with the hypocentrum. Beyond the articular head the stout shaft of the ribs is constricted for a short distance into an oval form, and then suddenly expands into the large flat or outwardly concave portion for union with the ilium. This thinned expansion of the first rib has an emargination on the upper posterior border, in which fits loosely the lower anterior border of the second rib, the two forming an elongated, nearly plane surface, which extends the whole length of the lower part of the ilium in its greatest width nearly opposite the upper part of the acetabulum. The first sacral hypocentrum is rather larger than the preceding one, with a parapophysial facet at each side for the rib. The second hypocentrum, of nearly equal size, has also a like facet for the rib on each side. The neurocentra of these two vertebræ are in part missing, apparently due to some accident before fossilization.

TAIL

The tail was preserved complete, but the flattened end was slightly disclocated, doubtless due to its thin, compressed form. The small bones of the neural side of the first six, or pygal, vertebræ were so small and so confused in the matrix that not much could be made of them. The six pygal hypocentra were found attached in a continuous series. There is a slight, very slight, possibility than an additional one may have been lost in the matrix at the place where the dislocation occurred, but I think not. The tail could not have been more than a fourth of an inch longer or shorter than is shown in the restoration and plate. The first six, or pygal, hypocentra decrease rapidly in length. With the fifth is a short, rudimentary rib, a mere pointed tubercle, and several similar ribs were found loose in the matrix.

Beginning with the seventh, or possibly the eighth, caudal there is a continuous series of fourteen or fifteen with chevrons, some of them, as shown in the drawings, with the neural arches attached. It required a critical examination with a lens to distinguish the very small pleurocentra of the posterior ones; that I did distinguish them I am quite certain. The hypocentra are angular; the lower posterior part extended into stout chevrons, which were perforated near their base for the hæmal canal. The distal part of the tail was thin and high, possibly used as a rudder-like organ in life.

RIBS

(Plate 12, figure 8)

Many of the ribs have been removed from their encrusting matrix with but little or no injury; some of the posterior ones, because of their extreme delicacy, could not be worked out completely. The first eight pairs have broadly expanded proximal extremities, with a distinct separation, save of the first pair, of the rounded and thickened capitulum from the more elongated and thinner tubercle. The upper border is nearly straight or gently convex on the proximal portion, convex beyond; for the three distal fourths or more the shaft is slender, gently flattened, oval in cross-section, and is curved downward. Beginning with the ninth rib, the proximal expansion is much less, and there is no distinction into capitular and tubercular articulations; the shaft is more slender. The ribs increase gradually in length to the ninth and probably to the tenth. Beyond this they decrease more rapidly in length. In the last two pairs, at least, they are reduced to tuberculiform rudiments, ending pointedly, and are apparently coösified with the diapophysis.

From the tenth to the eighteenth only the proximal parts were worked out—that is, their precise lengths could not be determined.

SIGNIFICANCE OF HYPOCENTRA AND PLEUROCENTRA

Two views have been and yet are held by morphologists as to the morphological significance of the pleurocentra and hypocentra of the rhachitomous amphibians. The first, that of Cope and Baur,[7] is that in the evolution of the higher vertebrates the pleurocentra progressively developed to form the centrum, while the hypocentrum as progressively

[7] Cope: Transactions of the American Philosophical Society, vol. xvi, p. 243. Baur: Biologis. Centralbl., vol. vi, 1886, p. 12; American Naturalist, 1897, p. 975.

diminished, leaving a vestige only in the intercentrum of the modern *Sphenodon* and other reptiles, and possibly certain mammals. On the other hand, Cope, at least, believed that the pleurocentra disappeared in the holospondylous and modern amphibians, the hypocentrum persisting as the centrum.

The other view, that of various authors, notably Gaudry, Goette, Gadow, Jaekel, and Broili, is that the pleurocentra and hypocentrum fuse to form the centrum of all the higher vertebrates.

Unfortunately, both of these views must remain as hypotheses until, it is hoped, some fortunate discovery of intermediate forms may confirm or reject one or the other or both. In favor of the second view, which has been well presented by Broili,[8] it is seen (plate 12, figure 5) that the pleurocentra articulate with each other in the middle, inclosing below and between them and the hypocentrum a notochordal perforation, quite analogous, perhaps homologous, with the central perforation in all primitive holospondylous vertebræ. With a close fusion of the four elements of the vertebræ and obliteration of the sutures a rhachitomous vertebra would be practically indistinguishable from a notochordal vertebra of the early reptiles. Moreover, the presence of distinct elements in the primitive cartilaginous vertebræ of the chick, in addition to the arch, assumed to be pleurocentra and hypocentra, would suggest their persistence closely fused in the ossified centrum.

This explanation would seem to be the most reasonable of any, especially if we had to deal with the modern amniota alone. Unfortunately, there are objections, ones recognized by Cope and Baur, which complicate matters. In the first place, this theory would necessitate the recognition of a morphological distinction between the intercentra as originally so called by Cope, and as found in the living *Sphenodon*, and the primitive hypocentra. It is a well known fact that intercentra are far more prevalent among the old forms than the modern ones; that practically all reptiles with notochordal perforations possessed them, while only vestiges are found among modern reptiles save *Sphenodon*, leaving for the present the chevrons out of account. In the modern crocodilia alone has every vestige of them disappeared back of the atlas, while the lizards possess them throughout the neck, and turtles have at least one or two back of the atlas. If they are morphologically distinct elements, what explanation can be given for their origin and wide prevalence among the early reptiles and their gradual disappearance in the modern forms? They are known only in the amniota. Neither of the

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[8] Monatschr. d. Deutschen Geologisch. Gesellsch., ix, 1908, p. 236.

views as to the fate of the pleurocentra will militate against the commonly accepted theory of the structure of the atlas, where the united pleurocentra do not fuse with the hypocentrum, but remain distinct as the odontoid process of the axis. But we have in such forms as *Dimetrodon*, as well as all other Permian reptiles, to say nothing of the modern lizards, a very large element, often larger than the atlantal hypocentrum itself, intercalated between the atlas and the body of the axis below. If it be an intercentrum purely, it has assumed enormous proportions, suggesting very forcibly the original size of the intercentra throughout the column. If it be a hypocentrum like that of the atlas, we are irresistibly driven to the conclusion that either the body of the axis is its pleurocentra, or else that the pleurocentra and neurocentra of an intercalating vertebra have disappeared between the axis and atlas, leaving only the large hypocentrum. And if this hypothesis be true, then a like explanation would be necessary to account for all the intercentra, which certainly are morphologically identical with the intercalating element in *Dimetrodon*. But such a theory is altogether too tenuous for me. It may be all very well to account for the ossifications between the centra in *Sphenodon* as new elements originating from one knows not what and call them intercentra or subcentra, as Jaekel has very superfluously renamed them, but will some one give a reasonable explanation of the very large preaxial intercentrum in *Dimetrodon* and the other early reptiles, as well as the lizards, on this hypothesis?

Again, it is a remarkable fact, for which no reasonable explanation has ever been given save by Cope, that in all true amphibians, both ancient and modern, the chevrons are an integral, inseparable, exogenous part of the body of the vertebræ, while in all reptiles and higher vertebrates they are the intercentrum or part of it. In other words, they are in all rhachitomous and embolomerous amphibians a part of the hypocentrum, a prolongation of its lower part, perforated for the passage of vessels, immovably united, while in all amniota they are freely articulated between the vertebræ, or, as in some lacertilia, with the posterior part of the body itself. Free chevrons have never been discovered in true amphibians, and until they are we are compelled to assume that they are the hypocentra, and thus, under the second hypothesis, must be morphologically distinct from the chevrons of the amniota which are attached intercentrally.

It is a remarkable fact that intercentra have never been discovered in any amphibian, ancient or recent. In the Microsauria we have in some cases well developed vertebræ associated with a fully ossified skeleton, but so far no intercentra have been discovered in this group, so far as I am aware, nor free chevrons, save in *Hylonomus*. Again, the primitive rib in the reptilia was articulated invariably with the intercentrum and neurocentrum, and never with the centrum exclusively. In the rhachitomous amphibia the articulation as seen in the present form was with hypocentrum and neurocentrum. Probably that was the invariable rule, for I know of no amphibian in which the capitulum of the rib articulated between the centra. This fact is suggestive, at least.

Yet, further, in the embolomerous forms it is the pleurocentra which become detached from the remainder of the vertebra to form an independent disk between the hypocentra, just as is the case in the atlas of the amniota.

I am fully conscious that the theory of the hypocentral origin of the centra of modern amphibians and the exclusively pleurocentral origin of the same of the amniota seems a bit improbable, though, of course, not impossible; I am not ready to receive it as a safe theory yet; I am still less ready to accept the theory of the independence of intercentra and hypocentra morphologically, as the other theory demands.

On a later page of this article I give the description and figures of a remarkably amphibia-like reptile, in which the vertebral structure seems to be intermediate between the rhachitomous and the reptilian type. It is not decisive, but is very suggestive.

PECTORAL GIRDLE AND EXTREMITY

Scapula coracoid.—The scapula coracoid (plate 10, figure 1; plate 11, figure 1) is a relatively large bone, with no indications of sutural division into its supposed component parts. The blade is moderately expanded above, gently concave on its outer, convex on its inner, surface. Its upper border is a little convex longitudinally, its edges sharply truncate for cartilage. The posterior border is thickened to the beginning of the glenoid concavity; the corresponding anterior border is thinned.

The posterior border divides to include the supraglenoid fossa, perforated at its bottom by the supraglenoid foramen. The outer border continues downward, and by a gentle curve backward to terminate in the oval preglenoid facet, which looks downward, backward, and outward. The inner margin, the thicker, extends downward, inward, and backward, with an anterior curvature. In one specimen the end is angularly truncate, in all probability for a small metacoracoid that was not ossified. In the others it continues in a thin border back of the margin of the posterior glenoid facet. This latter facet is near the lower part of the bone, an elongate concave surface, with sharp margins posteriorly, and is opposed to the anterior facet already described. Between these two facets and a little above them the glenoid foramen pierces the bone obliquely backward to open on the inner surface a little back of the border of the subscapular fossa, in which the supracoracoid and the supraglenoid foramina both open. The lower anterior part of the bone is thickened, with truncate edges, and is convex in outline. The upper end of the cartilagious border continues backward as an angular thickening, nearly on a level with the upper border of the preglenoid facet. The thickening extends as a ridge a short distance backward. In much probability this ridge limits the upper border of the epicoracoid, since in the immature specimen already spoken of a sutural line seems to run directly backward below the upper edge of the preglenoid facet, quite as in *Varanosaurus*. The lower edge of the preglenoid facet continues as a rounded border downward and forward part way to the lower margin of the bone. In the cavity thus formed at the lower end of the facet is the opening of the supracoracoid foramen. On the inner surface of the bone, near the middle, extending downward subparallel with the anterior border of the bone, is the anterior border of the subscapular fossa. In its middle part the free border overhangs a deep fossa looking backward, at the upper end of which opens the supraglenoid foramen; at the lower end is the opening of the supracoracoid foramen. Back of this margin the bone is convex, and is pierced by the inner opening of the glenoid foramen.

Cleithrum.—The cleithrum, found in position on either side, is remarkable for its large size. Its lower part is a long rod closely attached to the anterior margin of the scapula as far as the angular thickening I have described; it is overlapped through nearly its whole extent by the upper part of the clavicle. The upper part of the cleithrum is broadly dilated and thin, covering the upper border of the scapula to its hind angle and arched inward. Its borders are very thin, convex above, concave below; the posterior thin margin is nearly straight. The bone above forms a sort of roof, convex outwardly, concave inwardly.

Clavicles.—The clavicles are small, somewhat spoonshaped, with curved handle. The upper, slender part is closely applied to the outer, anterior side of the lower, rodlike part of the cleithrum, reaching nearly to the dilated portion. The lower end, curved inward and a little backward, is dilated with thin margins, concave on the inner side where it articulates with the interclavicle, convex on the exterior or lower surface. It underlaps the interclavicle and partly covers the lower anterior border of the epicoracoid.

Interclavicle.—The interclavicle is a small, thin bone dilated and thinned in front where it overlies the ends of the clavicles, which touch in the middle. The posterior extension or "stem" is short, not as long as the expanded part.

Humerus (plate 11, figures 2-5).—The humerus is of the usual temnospondyl form, differing from that of *Eryops* and *Trematops* especially in the absence of the ectepicondylar process, so conspicuous in the former and in *Euchirosaurus.* It is broadly expanded at either extremity in planes nearly at right angles with each other, and has a rather slender shaft in the middle. The lateral or radial process is very stout; the medial or ulnar process is indicated by a slight ridge or elevation just below and in front of the inner extremity of the proximal articular surface. The digital fossa on the inner side is rather shallow and broad. The short shaft is subcylindrical in cross-section, with a sharp ridge running from the outer side of the lateral process to terminate in the supinator ridge. The capitular surface for the radius is subhemispherical in shape, looking mainly forward. The trochlear surface for the ulna is small. The inner, condylar border is moderately dilated and relatively thin; the ectepicondylar or supinator border thick. There is no indication whatever of the ectepicondylar process below the lateral process on the outer side.

Humeri of allied forms.—Among the early land vertebrates no part of the skeleton is more characteristic than the humerus. As a rule, the humeri of the amphibia and reptiles resemble each other markedly—rather stout and short bones, with the extremities greatly expanded and their planes divergent from each other in an angle of from 60 to 90 degrees. Though usually thickset and short, in some of the reptiles it is as slender as that of existing lizards, an example of which is seen in the humerus of *Pleuristion,* a small cotylosaurian reptile—a little smaller than the existing *Sphenodon.* Climbing reptiles have slender humeri, fossorial and aquatic reptiles thickset and short humeri, though in some amphibious forms, such as the crocodiles, it is rather slender. In strictly terrestrial, cursorial reptiles it is never short and stout, from which it may be inferred that the amphibians and reptiles from Texas with such thickset humeri are either fossorial or aquatic. But it is an inference only, since there may be other causes to account for the robustness, of which we are not yet aware. One conclusion is, however, justifiable: animals with such humeri as are shown in plate 15, figures 4 and 5, were certainly not quick running in habit!

As a very general rule, the humeri of amphibians and reptiles may be distinguished by the absence of an epicondylar foramen in the former; its frequent presence in the latter. Among living reptiles the crocodilia have neither; *Sphenodon* has both ectepicondylar and entepicondylar foramina. Lizards frequently have an ectepicondylar foramen or groove; even the mosasaurs possess such a groove, though no record of it has hitherto been published. The Chelonia have, like the lizards, an ectepicondylar foramen or groove. Among the Amphibia an entepicondylar foramen was described by Cope in *Acheloma*, but an examination of the type specimen shows that while apparently present in one humerus, in its mate there is no indication of it, and the opening in the one may safely be ascribed to some accidental injury or malformation, especially so since its position and form are aberrant. So, also, *Euchirosaurus* has been restored with such a foramen, or rather with an ectepicondylar opening, but quite incorrectly so. The euchirosaurian humerus is of the strictly *Eryops* type, and like *Eryops* it does not have an epicondylar foramen. There are but two known amphibians, ancient or modern, with an epicondylar foramen, *Diplocaulus* and *Cochleosaurus*.

In the collections of the University of Chicago there are well preserved humeri of not less than ten genera of Texas amphibians. In addition to these I have examined the humeri of *Acheloma* and *Dissorophus*, and Broili and Case have figured the humerus of *Aspidosaurus*. Of four Permian genera the humerus is unknown—*Zatrachys*, *Anisodexis*, *Cardiacephalus*, and *Cricotillus*. The last-named genus is very doubtfully distinct from *Crossotelos*. *Anisodexis* is a large form, clearly allied to *Eryops*, and doubtless with a humerus similar to that of *Eryops*. *Cardiacephalus* is a very small amphibian, altogether too small to belong with any of the femora figured in plate 15. Of the remainder *Cricotus* may possibly be represented among the unidentified forms, but probably not, since nearly all the material in the Chicago collections are from the upper horizons, all of the humeri herewith figured, an horizon in which neither *Cricotus* nor *Zatrachys* occurs. One other genus may be mentioned, *Lysorophus*, of which evidence of limbs is found among the material in the collection, but the bones are small, almost minute. It thus is almost certain that we have evidence of at least fifteen genera of Permian amphibians from Oklahoma and Texas. I know of none from the reputed Permian of Illinois save *Diplocaulus* and *Cricotus*.

Of the humeri shown in plate 15 two certainly do not belong among the temnospondyles, those of *Crossotelos* (figures 2 and 3) and *Diplocaulus* (figure 7). Of *Crossotelos* I have seen a half dozen or more humeri from the Orlando bone-bed, always associated with vertebræ of the typical form and never with other forms. Its character was not recognized when first discovered, and the ends are unfortunately reversed in the drawings. It is a simple bone, moderately expanded at the extremities, with a rather deep concavity longitudinally behind, and with but a small lateral rugosity. All the specimens found show an incomplete chondral ossification. The form was doubtless more or less aquatic. *Diplocaulus*, the only known amphibian, save *Cochleosaurus*,[9] with an epicondylar foramen, has been referred to the Microsauria or Lepospondyli by Cope, Broili, and Jaekel, as also by myself provisionally, but, as I pointed out in a recent paper,[10] the mode of attachment of the ribs is quite unlike that of the typical microsaurs and like that of the modern salamanders. Doctor Moodie has, because of this character, erected the new order of Diplocaulia for the genus, and I believe the name is valid, though the rank of the group is open to dispute. *Crossotelos* Case, a form with holospondylous vertebræ, found associated with *Diplocaulus* at Orlando, has distinctly double-headed ribs, with the capitulum attached to a facet just back of the front margin of the vertebral centrum, the tubercle to the extremtiy of a short diapophysis. True microsaurs have single-headed ribs attached intercentrally, with the chevrons presumably attached also as in reptiles. In both *Diplocaulus* and *Crossotelos* the chevrons are quite like those of the true amphibians, exogenous processes from the middle of the centrum. But I am quite confident that at least two distinct groups have been associated among what are called Microsauria, and that one of them, with single-headed, intercentral ribs and intercentral chevrons, must be dissociated into a group more nearly allied, possibly identical, with the reptilia in a wide sense, while the other will remain among the amphibia. As I am not able at the present time to decide which of these groups includes the type form of the order, it is premature to attempt the solution of the problem by giving new names. This thing, however, may be said with assurance, neither *Diplocaulus* nor *Crossotelos* can be united with such forms as *Eosauravus copei* Will. (nom. nov., *Isodectes punctulatus* Cope in part, *Isodectes punctulatus* Moodie), or *Sauravus costei* Thevenin. *Crossotelos* has numerous slender ventral ribs, very much like those of *Labidosaurus* and *Captorhinus* (*Pariotichus*), of which I have found abundant evidence in new material from Texas.

The humerus of *Trimerorhachis* (plate 15, figure 6) departs markedly from the ordinary temnospondyle type, as do also the femora, in which the adductor ridge is represented by a mere line on the ventral side of the femur quite as in the reptiles, and unlike all other known Texas amphibians. It is also remarkable for the small size of the lateral process, which is separated from the head by a considerable free space. This process is divided for the attachment of the several muscles into two rugosities opposite each other on the front and hinder surfaces. The median process, usually feebly indicated in the amphibians, is clearly

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[9] Broili: Paleontographica, lii, p. 15, fig. 3*a*.
[10] Transactions of the Kansas Academy of Science, vol. xxii, p. 122.

seen in a small but prominent hooklike process on the inner posterior side near the head. The proximal articular surface is, it is seen, quite at the extremity, suggesting a limited range of motion as compared with other forms, and it is also the case with articular surfaces for the radius and ulna. Here, as in other cases, the absence of distinct condylar surfaces may be of generic value or merely ontogenetic. While, as is well known, many amphibians, both extinct and living, do not have a complete chondral ossification, leaving the articular surfaces throughout life composed of cartilage, yet it is also quite possible that such a condition found in fossilized bones may be merely indicative of juvenility. In *Trimerorhachis,* however, it seems certain that the character is one of maturity, since more than a dozen humeri and a score or two of other limb bones in the collection all present the same unossified condition. From all of which facts I think the conclusion is obvious that *Trimerorhachis* was an aquatic form, notwithstanding the slenderness of the humeri, which simply is an evidence of a short tail and limb propelling habits.

Three other humeri figured in plate 15 are certainly of new genera. Two of them, figures 4 and 5, are of the usual temnospondylous type, but a third (figure 1) may represent a new type of amphibian from Texas. This humerus, it is seen, is an unusually slender bone, with its articulations well developed. The lateral process is small and the condyles are feebly developed. The bone, as preserved, shows but a slight twisting of its proximal from the distal plane, which may be in part due to the conditions of fossilization, though I think not. The genus when it is better known will, I believe, be found to be of a slender terrestrial type.

The humerus shown in figures 4*a, b,* and *c* is remarkable for its massiveness and shortness, in both respects excelling any other which I know. Here also the chondral ossification is deficient, the articular condyles, both proximal and distal, being roughened, more or less concave surfaces, doubtless thickly covered by cartilage in life. The humerus shown in figure 5 was found associated with that illustrated in figure 4. It is more of the *Dissorophus* type, though distinctly different, as were also its femora found associated with it. It also has an imperfect chondral ossification.

All of the humeri so far described lack the peculiar process just above and to the outer side of the capitellar convexity, so characteristic of *Eryops, Euchirosaurus,* and apparently also *Trematops.* It may be called the ectepicondylar process, and seems to be homologous with a similar process found in the *Pelycosauria,* but hitherto unknown in the *Cotylosauria.*

In a future communication I shall give a similar comparative illustration of the humeri of the reptiles, of which there are in the collections of the University of Chicago 12 distinct forms, representing as many genera.

Radius (plate 14, figures 7-9).—The radius has a very slender shaft in the middle, and is broadly and thickly expanded at either end. The posterior border is nearly straight, the anterior deeply concave, the two lateral borders nearly symmetrically and deeply concave in outline, the extremities of nearly equal width and nearly transversely truncate. The proximal end has a groove on the posterior side thinning the inner articular surface.

Ulna (plate 14, figure 10).—The ulna is a remarkably slender bone in comparison with the radius—slender in comparison with the bone in other genera of Permian air-breathers. It has a slender and curved shaft on the distal three-fifths, the distal extremity only a little widened, with its greater diameter at right angles to the greater diameter of the proximal end. The olecranon is very slightly produced, and the articular surface for the humerus is oblique to both axes of the bones; the inner side of the proximal end is flattened.

Two bones of the proximal row of carpals with several phalanges were found close to the bones of the left forearm. They are relatively small. Their characters may be seen in the figures (plate 12, figure 3).

PELVIC GIRDLE AND EXTREMITY

Pelvis.—The pelvis (plate 12, figure 4; plate 13, figure 1) is very strong and stout, the two halves meeting in a very firm symphysis, which forms an obtuse ventral ridge most protuberant in the middle below the acetabulum. The pelvic cavity is deep and spoutlike, nearly semicircular in transverse outline, with the lateral margins anteriorly and posteriorly slightly flaring. The anterior border is emarginate in the middle, the sides convex in outline, with a notch. The posterior margin is slightly narrower than the anterior, and has a deeper emargination in the middle line, the sides somewhat thinner, with convex borders to the outer, somewhat angular margin. The posterior margin of each innominate is concave from the upper angle of the ilium, with a pronounced angular projection in the middle of the concavity at the junction of the ilium and ischium; this border is rather thin throughout. The front border is likewise concave throughout from the upper angle of the ilium, with a slight convexity below the middle at the place of junction between the ilium and pubis. This border is much thicker than the posterior, and flares outwardly below. The acetabulum is deep and large, with its greatest concavity below its middle. It has a distinct and rather protuberant rim, save at the upper posterior part. Its upper border on the ilium is marked by a small but distinct process overhanging the concavity. The lower margin on the ischium is very prominent, forming an angular projection to the full width of the bone, while the stout expansion of the pubis in front limits the deepest concavity of the acetabulum. The shape of the acetabulum would indicate that the chief pressure of the femur was directed nearly horizontally and a little backward. The lower rim is nearly horizontal, deeply concave antero-posteriorly, overhanging the almost horizontal outer surface below. The pubes flare outward on each side in front from a subangular line, running downward and inward through the inner orifice of the obturator foramen to either side of the median emargination of the front border. The triangular surface either side thus limited looks at an angle of about 45 degrees upward from the horizontal position of the pelvis and slightly inward, and is gently convex from side to side. The under surface on the sides of the conjoined pelvis is nearly horizontal laterally, descending in the middle into a broad obtuse ridge, broadest and deepest a little in front of the middle. In front the downward curvature of the pubes leaves a concavity, at the bottom of which is the external opening of the obturator foramen, very near the middle of the pubis antero-posteriorly, and opposite the greatest protuberance of the pubic margin, not far from the border of the acetabulum. The front border of the pubes is roughened for cartilage. The sutures separating the elements are very clearly shown in the present specimen. Those between the ilium and ischium and pubes begin on the margins near the middle of the convexities described and run downward to meet a little below the middle of the acetabulum, that for the ischium being a little longer than the one for the pubis. The puboischiadic suture runs directly inward through the deepest part of the lower margin of the acetabular rim, the length of the ischia below being about a fifth greater than that of the pubes. The depth of the lower pelvic border is due solely to the breadth of the symphysis, the upper surface of the pelvis in the middle showing no corresponding concavity.

Femur (plate 13, figures 2-5).—The femur is remarkable among temnospondyles for its slenderness and the great development of the adductor crest. The proximal articular surface has its transverse diameter but little greater than the antero-posterior one, narrower on the outer side, more convex on the inner, where the articular surface extends more on the ventral side. The digital fossa is small and shallow. The adductor crest arises near the upper part of the bone, is directed outward for a short distance, and then is nearly straight to its distal end near the lower fifth of the bone, and near the middle of the popliteal surface. The shaft of the bone for about the middle two-fifths is very slender, almost cylindrical, save for the crest behind, and is straight. The distal expansion of the bone begins a little above the lower fifth and is a little greater than the proximal one. The lateral linear concavities of the bone on the two sides are nearly symmetrical. The distal articular surface of the bone has sharp borders, indicating a considerable amount of cartilage. The end is much broader transversely than from before backward. The transverse tibial surface looks downward and a little backward and inward. The fibular surface is a little longer from side to side and looks markedly outward, backward, and downward. Its width in the inner side is more than one-half of the whole width of the extremity, with narrow extensions both in front and behind. The fibular condylar projection is much thinner and less extensive than the tibial. The extensor groove in front of the distal end is broad and moderately deep, limited on the outer side by a high and rather sharp ridge. On the back side a less prominent, more obtuse ridge opposite the dorsal ridge, and connected with the distal end of the adductor crest, separates a shallow concavity on the inner side from a narrower and deeper one on the outer side.

Tibia (plate 14, figures 1-4).—The tibia is more than three-fourths the length of the femur. Its upper extremity, as usual, is broadly expanded and massive, the lower less expanded and more cylindrical. The upper surface for articulation in the normal position of the bone is broad from side to side and about two-thirds as wide from before back, thicker on the outer than on the inner side, with an emargination on the outer anterior side, the anterior border internally convex, the posterior border nearly straight. The surface is gently convex from side to side, nearly flat antero-posteriorly, and looks on the whole upward and a little backward. The distal articular surface is suboval, its longer diameter running from behind outwardly and anteriorly, with the internal border convex, the outer posterior border more nearly straight or gently convex. The shaft is slender in its middle, broader in section from before backward, and is flattened on the inner side. The inner border of the bone is deeply concave, the outer almost straight, save at the lower end. The posterior surface of the bone is flattened on the upper expansion, bounded inwardly by a sharp sinuous crest, which becomes confluent with the convexity of the distal extremity.

Fibula (plate 14, figures 5 and 6).—The fibula is shorter than the tibia, flattened upon its posterior inner surface, and convex from side to side on the opposite. The outer thinner margin is nearly straight to the lower fourth, where it curves inward. The inner border is deeply concave, more so on the lower half. The lower extremity is more expanded than the upper, and is also thicker, strongly convex in front, and somewhat concave on the posterior surface. In the vertical position of the bone the upper articular surface is nearly horizontal, while the lower is directed at an angle of about 20 degrees inwardly.

Associated with the leg bones were found a number of tarsal and phalangeal bones, figures of which will be found in plate 12, figures 1 and 2. Their precise position can not be determined, more than that two of the tarsals belong in the proximal row and three of the toe bones are metatarsals.

Taxonomy

DISSOROPHUS MULTICINCTUS

From West Coffee Creek, in Baylor County, I was so fortunate as to find a considerable part of a skeleton of *Dissorophus multicinctus*, which adds not a little to our knowledge of this genus. The parts preserved are the nearly complete skull, with the palatal region imperfect, the nearly complete carapace, with several vertebræ attached, the nearly complete pectoral girdle, humeri, parts of the radius and ulna, the imperfect pelvis, a femur, parts of the tibiæ, and several tarsal bones. They will be figured and described soon by the writer. The skeleton agrees in its essential characters closely with *Cacops*, but is generically distinct in the much greater development of the carapace, with its fused anterior dermal bones, armadillo-like, and in the much greater stoutness of the appendicular skeleton. From this specimen and the material of *Cacops* may be given the following family and generic characters. In the family characters I italicize those based exclusively upon *Cacops*.

DISSOROPHIDÆ—FAMILY NEW

General characteristics.—Skull with the otic notch completely enclosed to form a large ear cavity. Palate with but two large teeth on each side, one at the anterior inner margin of the nares, the other at the posterior margin; mandibular and maxillary teeth of nearly equal size. Parasphenoid reduced. *Twenty-one presacral vertebræ; two sacral vertebræ; tail short.* A dorsal carapace, composed of lateral expansions of the spines of the vertebræ, with overlying intercalated dermal plates. Cleithrum very large and expanded above. Clavicles small, without exterior pittings. Interclavicle smooth on the dermal surface, small, with a short posterior process. Humerus without ectepicondylar process. Femur with strong adductor crest.

Genus Dissorophus Cope.—Dermal carapace extending the full width of the body, with a broad and elongated shield in front covering several vertebræ. Cleithrum less expanded and thicker. Scapula much expanded antero-posteriorly below. *D. multicinctus* (*articulatus*) Cope.

Genus Cacops Williston.—Dermal carapace but little wider than the vertebræ, narrowed in front and not fused into an anterior shield. Cleithrum thin and more expanded. Scapula less expanded below, the interclavicles and clavicles more slender. *C. aspidephorus* Will.

TREMATOPSIDÆ—FAMILY NEW

It is very evident that the characters of *Trematops* as given by me[11] are of more than generic importance. The genus represents a distinct family, which may be defined as follows:

A median foramen back of premaxillæ; large antorbital vacuities. Otic notch wholly enclosed by bone, the opening small and extending far forward. Palate with two pairs of large teeth back of the nares and a single one on each vomer. No parasphenoid. Ribs short, the anterior ones expanded distally. Twenty-two or twenty-three presacral vertebræ; a single sacral; tail short. No dermal armor or carapace. Cleithrum unknown. Clavicles and interclavicle small, without dermal pittings. Humerus with ectepicondylar process. *T. milleri* Will.

Restoration

(Plate 17)

The figures of *Cacops aspidephorus* given in the following plates and the mounted skeleton of plate 17 are nearly all from a single specimen, found with all of its parts intact and closely related in the matrix, lying in a prone condition. It was lying near the right side of one of the blocks of clay, taken up with the aid of bandages, and in separating the blocks some fragments of the right limbs were probably lost; the remainder probably are yet lying in the adjacent block, but the time required to work out each of these separate blocks, with their numerous skeletons and parts of skeletons, has rendered it inadvisable to wait till the whole material has been prepared before publishing, especially as but very little new information is to be gained. Inasmuch as the other skeletons exhumed are of a slightly larger or smaller size, their bones have not been used to replace the tibia and fibula, radius and ulna, and feet of the right side, which have been modeled in plaster from the left side. Numerous

[11] Journal of Geology, July-August, 1909, p. 389.

foot bones have been found dissociated, and probably a large part of the material must be worked over before the feet are found in all their natural articulations, inasmuch as it required the working out of six or seven feet and four or five hands of *Varanosaurus* from the same blocks before every detail of the structure of the extremities of that genus was determined. The foot bones thus have been arranged in the mounted skeleton after those of *Trematops* and *Eryops*, and it is quite certain there can not be much error. Nevertheless, it is expected that even these details will be determined in the course of a year or two. As is stated in the description, the precise lengths of the tenth to the eighteenth ribs could not be determined from the single specimen, as also the precise structure of the arches of three or four of the proximal caudal vertebræ. These have been restored, and it is not at all probable that the real bones when found will make any discernible difference in the mounted skeleton.

Everything else, to the smallest details of the mounted skeleton, is bone; the only plaster used was that necessary to cement the pieces together when broken in preparation. Furthermore, the posture of the skeleton is almost exactly that of the fossil as it was preserved in the matrix. Upon the whole I doubt whether there is another mounted skeleton of an extinct reptile or amphibian about which there is so little of error or with so little restoration as the present one.

The creature as mounted presents an almost absurd appearance, with its large head and pectoral region, absence of neck, and short tail. It is very certain that it possessed no other dermal ossifications than those of the median dorsal carapace, and it would seem almost as certain that the creature was aquatic or largely amphibious in its habits. Almost froglike in appearance, it doubtless had more or less froglike habits. What the significance of the dermal carapace was I am at a loss to suggest. That it could have been of protection to the creature seems more than doubtful, whatever may have been its use in *Dissorophus*, where it covered the whole dorsal region. But this coincidence is remarkable: With an external turtle-like ear opening, it had also the beginning of a turtle-like carapace. And this parallelism is also seen in *Diadectes*, a reptile with dorsal dermal plates and turtle-like ears. It is quite possible that the toes may have been a trifle longer than they are shown in the mounted skeleton—that I hope to determine later, but it is not probable, judging from the considerable number of phalangeal bones that have been found with the skeletons. That the animal was a swimmer I do not doubt, and in all probability the feet were webbed—they were certainly not clawed. Whatever may have been the habits of the creature, it, with its nearly related *Dissorophus*, must be classed among the oddities of vertebrate paleontology.

Desmospondylus anomalus—Genus and Species new

(Plate 16)

The specimens representing a peculiar type of reptiles, which I am constrained to regard as new, were discovered by Mr. Paul Miller within a few rods of our camp on West Coffee Creek, Baylor County, Texas, from about the middle portion of the Permian beds. A series of small vertebræ was found partly protruding from the clay, about 6 inches below another specimen of larger size, which was recognized as a species of *Trimerorhachis*. Many of the fragments of both specimens had been intermingled in the wash, and several hours were spent in carefully removing the clay containing them and washing out the fragments in the near-by Coffee Creek. The bones, fortunately, were firm and hard, and entirely free from matrix, though broken into many fragments. A study of this loose material discloses a large part of a skeleton of *Trimerorhachis* and numerous fragments belonging to the present species. The mass of clay taken up with bandages included the series of about a dozen vertebræ, with two humeri, right and left; two ilia, also right and left; a femur and two tibiæ, right and left, with a portion of a fibula and several phalanges. In addition a part of a large interclavicle was also found in the clay matrix. In the wash were found another humerus, a femur, two ilia, and a radius, and probably fragments of ulnæ and tibiæ, all of a slightly larger size, though otherwise agreeing closely with the corresponding bones found in position, or nearly in position, in the matrix. Whether this second specimen had been originally associated with the other in the same horizon, whether it was associated with the *Trimerorhachis*, or whether indeed it came from still a higher horizon, it is impossible to say.

In addition to this material belonging to one species, another femur nearly twice the size and more slender in form, though otherwise quite similar, was found a few weeks later associated with the remains of *Cacops*, described in the present paper. Its horizon was probably nearly that of the present species. From the famous bone-bed of Danville, Illinois, Mr. Gurley obtained, a good many years ago, a large and well ossified humerus which has long been a puzzle. Case figured this specimen, without assigning it to any known genus, in his paper on the Illinois specimens in the Journal of Geology, volume VIII, plate III, figures 4*a*, 4*b*. It has long been considered an amphibian, notwithstanding the presence of an entepicondylar foramen. It unquestionably belongs in the present genus.

The University of Chicago collection of Permian vertebrates from Texas and Oklahoma now includes representatives of at least 26 genera, all of which I know more or less well. Five or six of the genera described from Texas and Oklahoma, some of them on fragmentary material, I have so far not identified, though I have seen the types of several. They are *Cricotillus* Case, of doubtful validity; *Seymouria* and *Cardiacephalus* Broili; *Isodectes, Pantylus,* and *Anisodexis* Cope. It is, hence, possible that our genus may be identical with some one of these, but the probability is so slight that I have no hesitation in giving the new generic and specific name to the present specimens.

The vertebræ, of which there are 20 or more centra and fragmentary arches, in addition to the connected series of 7 or 8, present some extraordinary characters—characters which are very suggestive of amphibian affinities, annectant between the rhachitomous and holospondylous types. The centra, coming all of them apparently from the posterior dorsal region and the tail, are short, almost disklike, deeply concave, with a small perforating foramen. The arches are entirely free; the sutural surface for their attachment is extensive, situated on the anterior three-fourths of the centrum and extending downward on the front margin to below the middle. Back of this sutural surface there is a similar beveled surface extending about one-fourth of the length of the centrum, which also reaches down on the posterior side to the middle of the centrum. The arches are very low, with a rudimentary spine only, resembling the arches of *Labidosaurus* or *Captorhinus.* The zygopophyses are very large and broad, with their surfaces nearly horizontal. Below and back of the anterior zygapophyses there is, on either side, a distinct diapophysis, on the more anterior vertebræ standing out prominently, on the posterior ones a mere rugosity. Lying by the sides of these processes were a number of small ribs, which seem to have been single-headed, inasmuch as no double-headed ribs were found in the matrix. However, as *Labidosaurus* has quite this form of diapophyses posteriorly with double-headed ribs, it is not impossible that such was the character of the ribs in this genus.

The anterior border of the pedicel, beginning low down, projects forward, so that if two vertebræ were closely applied the arch would rest on two centra, though chiefly on the posterior one, and, so far as I can determine from careful measurements, this would be the case with the zygapophyses closely interlocked.

That this was not the condition ordinarily, however, is rendered certain by the presence of extraordinarily large intercentra found in position between several of the centra. Relatively, as compared with the centra, these intercentra are the largest known in any vertebrate, suggesting impressively the lower half of the pleurocentra of *Cricotus*. When in position they reach upward to the middle of the centrum, and almost or quite touch the extremities of the arch. (See plate 10, figure 3, and plate 16, figures 8-12.) If the ribs were double-headed the capitulum must have articulated with the upper ends of the intercentra. These intercentra are narrower above, so that there is left a distinct free space between the upper parts of the adjacent centra in the horizontal straight position of the column. When curved upward, however, the arches would fill the interstice between the contiguous vertebræ, leaving a wedge-shaped space below filled with the intercentrum. Some of the centra preserved are hardly more than half the diameter of the largest. They are evidently caudal vertebræ, though no indications of chevrons have been discovered. Others are even more disklike than the ones figured, resembling so closely various centra attributed to *Cricotus* from the Illinois deposits, that it is probable that they really belong in this genus and are centra, rather than to *Cricotus*, especially so as they agree in size with the femur mentioned above.

Not only are the vertebræ so curiously intermediate between the ordinary reptilian type and the embolomerous type, but the limb bones, both humeri and femora, were referred unhesitatingly to the amphibians before the vertebræ were recognized. The humerus (plate 16, figure 1) is extraordinarily stout and rugose for its length. Immediately below the lateral process there is a stout process, hitherto characteristic of certain temnospondylous amphibians, which I have called the ectepicondylar process, most characteristically seen in *Eryops* and *Euchirosaurus*. No such process is known in any Permian reptile, certainly in no Cotylosaurian. Furthermore, the median process is developed into a stout protuberance, quite as in *Eryops*. On the other hand, there is an entepicondylar foramen, remarkable for its large size, known only among amphibians in *Diplocaulus* and *Cochleosaurus*, wholly unrelated forms.

The femur (plate 16, figures 4, 5) also is remarkably amphibian in character in the extraordinary development of the adductor crest, a character known in no other Permian reptile. The digital fossa is extraordinary for its extent and depth, reaching nearly to the middle of the bone. The bones identified as tibia and radius (the former was found close to the femur and ilium, the latter in the wash) present no peculiar characters, though remarkably stout and robust (figures 2, 3).

Among the material in the wash are fragments of a small skull mingled with *Trimerorhachis* skull material, but there is too much doubt of their reptilian character to make it worth while describing them until further evidence of their identity is forthcoming.

That the present genus is not a pelycosaurian is, of course, evident; its relationships with the cotylosaurians are more apparent. Nevertheless, the great differences in the structure of both vertebræ and limb bones from anything known among either the diadectid or pariotichid types render the exact position of the genus very doubtful. Possibly, as I have said, it may eventually turn out to be congeneric with some one of the few forms in which the vertebræ and limb bones are yet unknown, especially *Pantylus*.

Explanation of Plates

All the figures are by the author, from specimen number 647, and of natural size, save where otherwise noted

Plate 6.—*Cacops aspidephorus* Will. Top view of skull. Specimen number 649.

Plate 7.—*Cacops aspidephorus* Will. Palatal view of skull. Specimen number 649.

Plate 8.—*Cacops aspidephorus* Will. Figure 1, side view of skull; specimen number 649, except posterior part of mandible; figure 2, upper view of left mandible.

Plate 9.—*Cacops aspidephorus* Will. Vertebral column, from right, with sacral ribs.

Plate 10.—*Cacops aspidephorus* Will. Figure 1, scapula, with attached cleithrum and clavicle; *a*, from within; *b*, from without; figure 2, *Aspidosaurus* sp. Broili, spines of dorsal vertebræ; *a*, from the left; *b*, from in front; figure 3, *Desmospondylus anomalus*, posterior dorsal vertebræ; *a*, from the left; *b*, intercentrum from below; both figures twice natural size.

Plate 11.—*Cacops aspidephorus* Will. Figure 1, pectoral girdle from above; figure 2, left humerus, from inner side; figure 3, the same from outer side; figure 4, the same from in front; figure 5, the same from behind.

Plate 12.—*Cacops aspidephorus* Will. Figure 1, various toe-bones of left hind foot; figure 2, tarsals of same foot; figure 3, carpals and phalanges of left front foot; figure 4, pelvis, from below; figure 5, twelfth vertebra, from in front, the left pleurocentrum omitted; figure 6, dorsal shield of same vertebra; *a*, from above; *b*, from below; figure 7, hypocentrum; figure 8, ribs, as numbered, 3 and 5 of the left side, the others from the right.

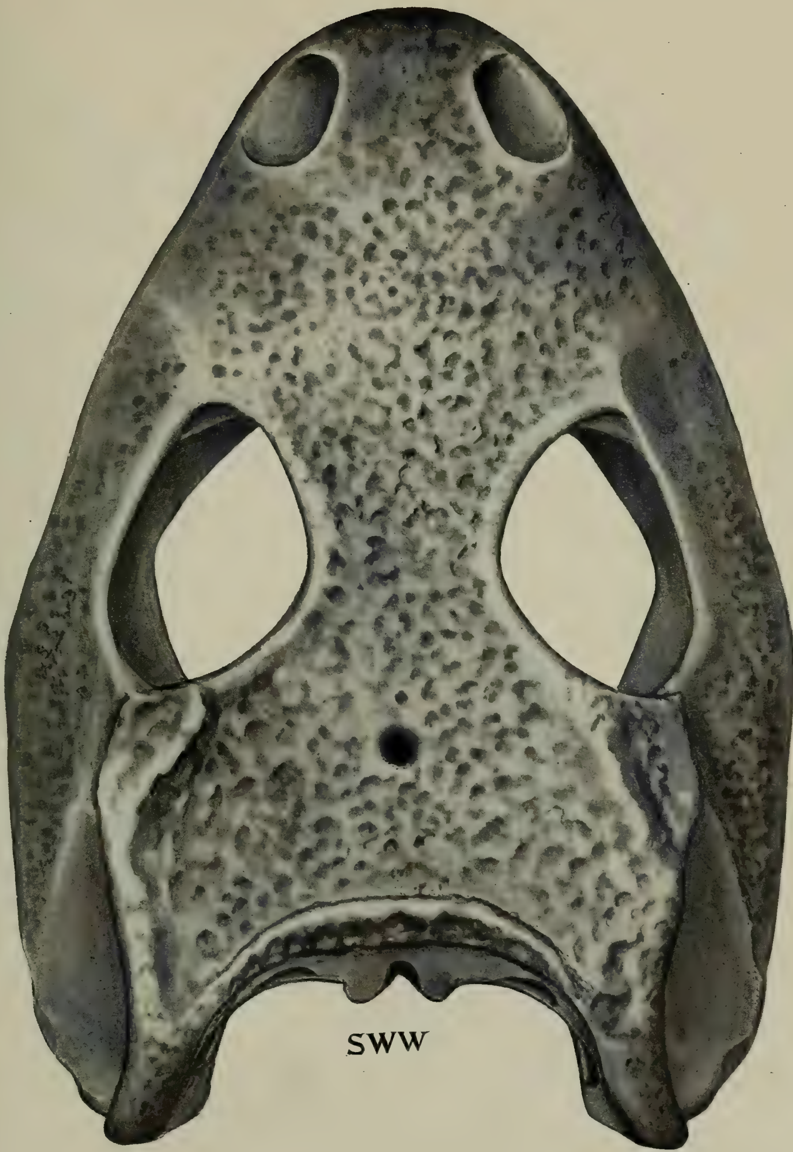
Plate 13.—*Cacops aspidephorus* Will. Figure 1, pelvis, from the right; figure 2, left femur, from in front; figure 3, the same, from behind; figure 4, the same, from within; figure 5, the same, from without.

PLATE 14.—*Cacops aspidephorus* Will. Figure 1, left tibia, from in front; figure 2, the same, from behind; figure 3, the same, from within; figure 4, the same, from without; figure 5, left fibula, from behind; figure 6, the same, from in front; *a*, upper extremity; figure 7, left radius, from behind; figure 8, the same, from in front; figure 9, the same, from within; figure 10, left ulna, from in front; figure 11, *Dissorophus multicinctus*, atlas; *a*, from behind; *b*, from in front; *c*, from the side; *d*, from below; figure 12, anterior hypocentrum, twice natural size.

PLATE 15.—Figure 1, genus new, right humerus; *a*, from in front; *b*, from behind; figure 2, *Crossotelos* Case, left humerus, reversed, from behind; *a*, the same, from in front; *b*, the same, distal end; *c*, the same, proximal end; figure 3, *Crossotelos*, right humerus of another specimen, reversed, from behind; figure 4, genus new, right humerus; *a*, from in front; *b*, from behind; *c*, proximal end; figure 5, genus new, left humerus, from behind; figure 6, *Trimerorhachis* Cope, left humerus; *a*, from behind; *b*, from in front; figure 7, *Diplocaulus* Cope, right humerus, from behind.

PLATE 16.—*Desmospondylus* Will. Figure 1, *D. anomalus* Will., right humerus; *a*, from side; *b*, from in front; figure 2, *D. anomalus*, tibia; figure 3, *D. anomalus*, radius; figure 4, *D. anomalus*, right femur, from behind; figure 5, *Desmospondylus*, sp. n., left femur, from in front, natural size; figure 6, *D. anomalus*, fibula; figure 7, *D. anomalus*, left ilium, from without; figure 8, *D. anomalus*, vertebra, from in front; figure 9, *D. anomalus*, centrum, from behind; figure 10, the same, from in front; figure 11, the same, from above; figure 12, the same, from the left side; all figures, save 5, twice natural size.

PLATE 17.—*Cacops aspidephorus* Will. Mounted skeleton; specimen number 647; one-third natural size.



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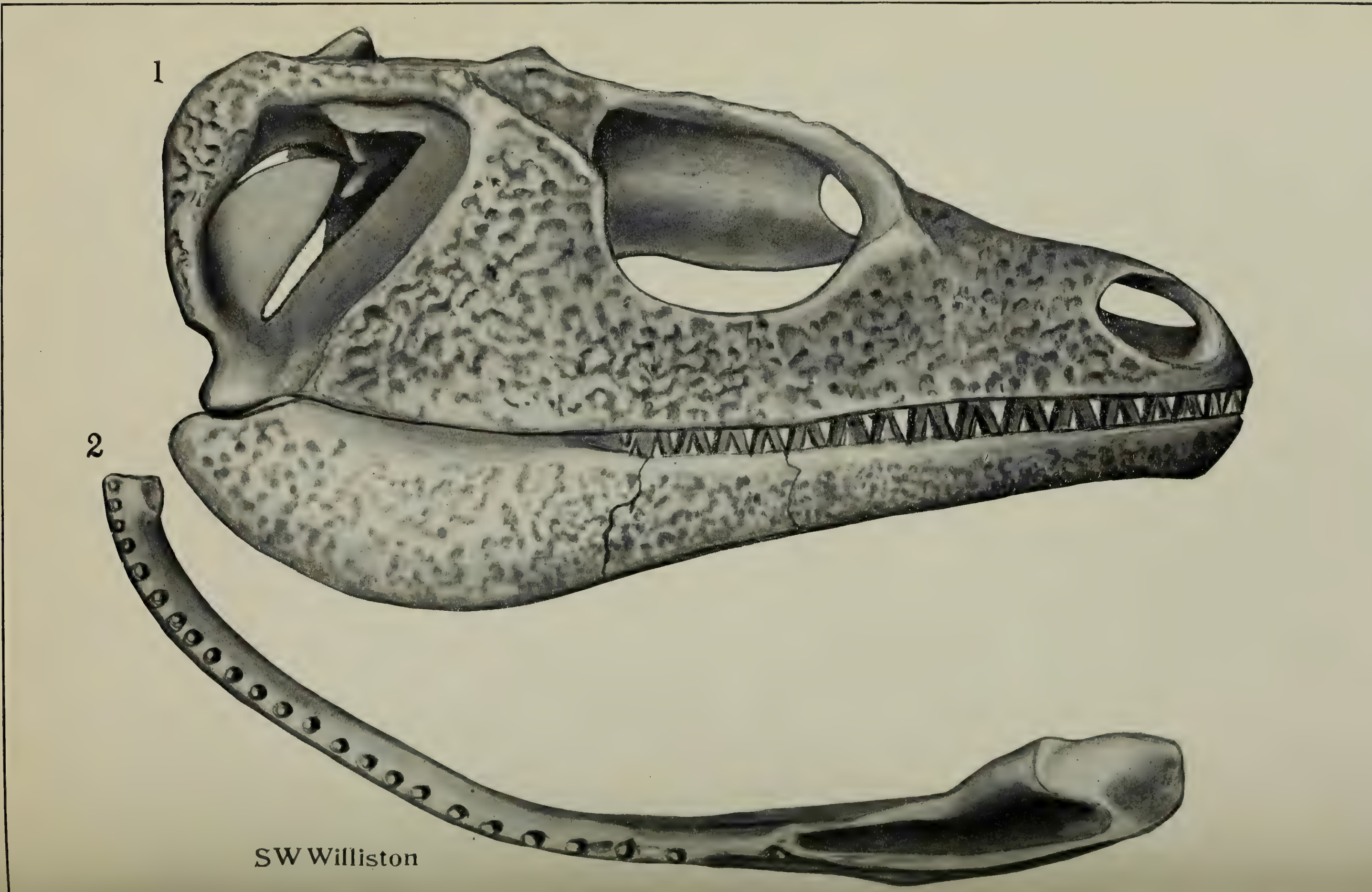
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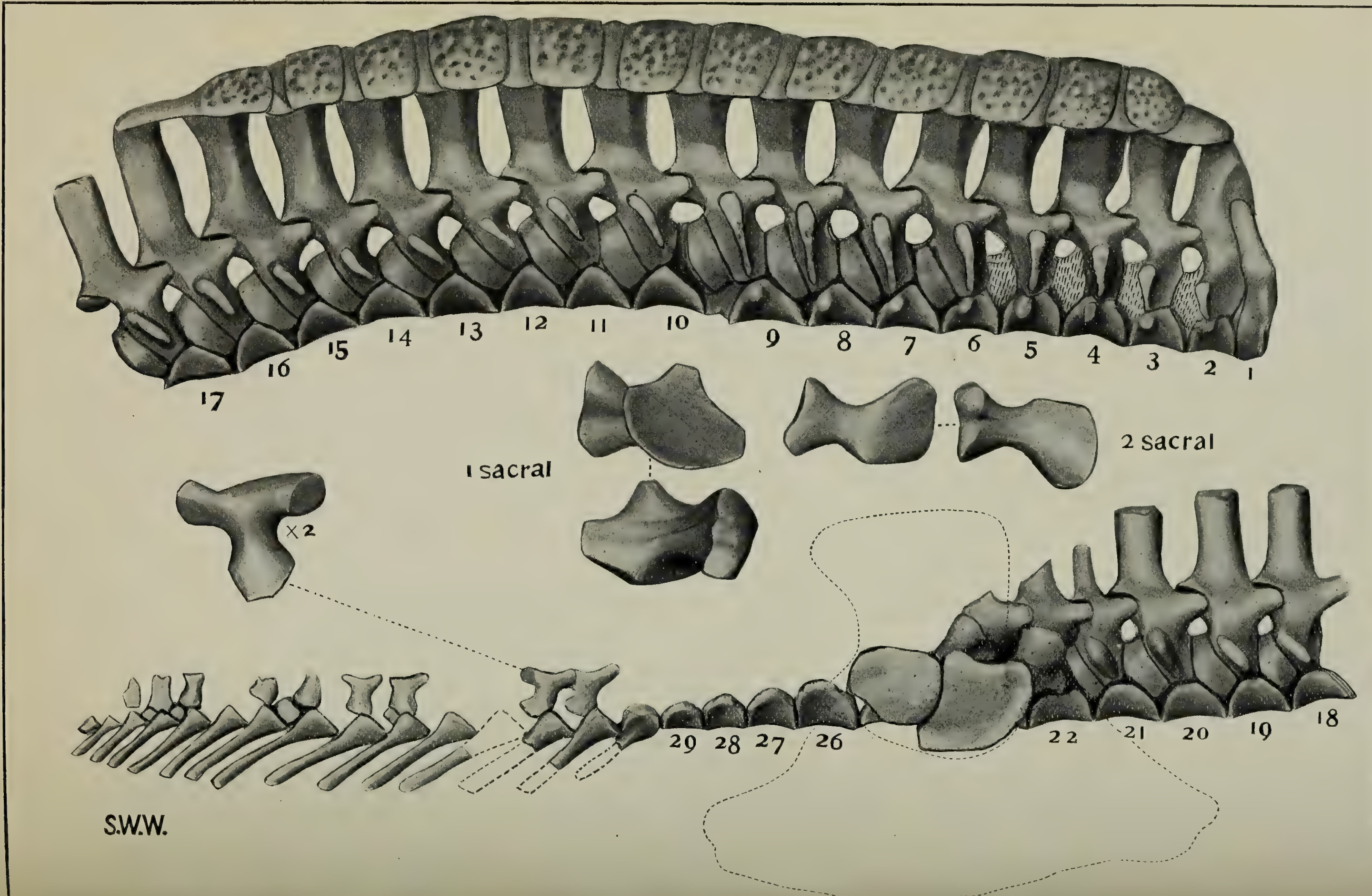
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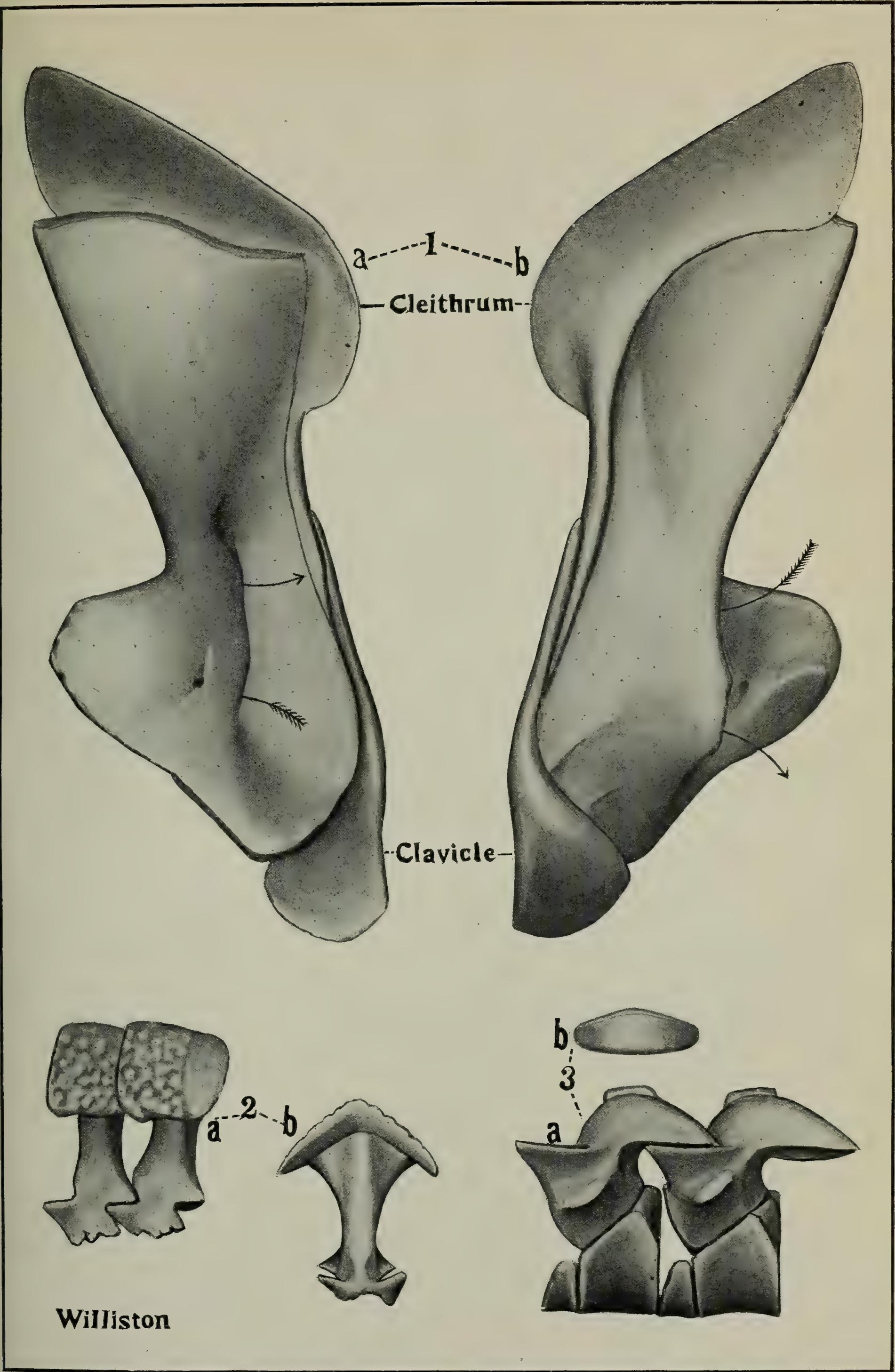

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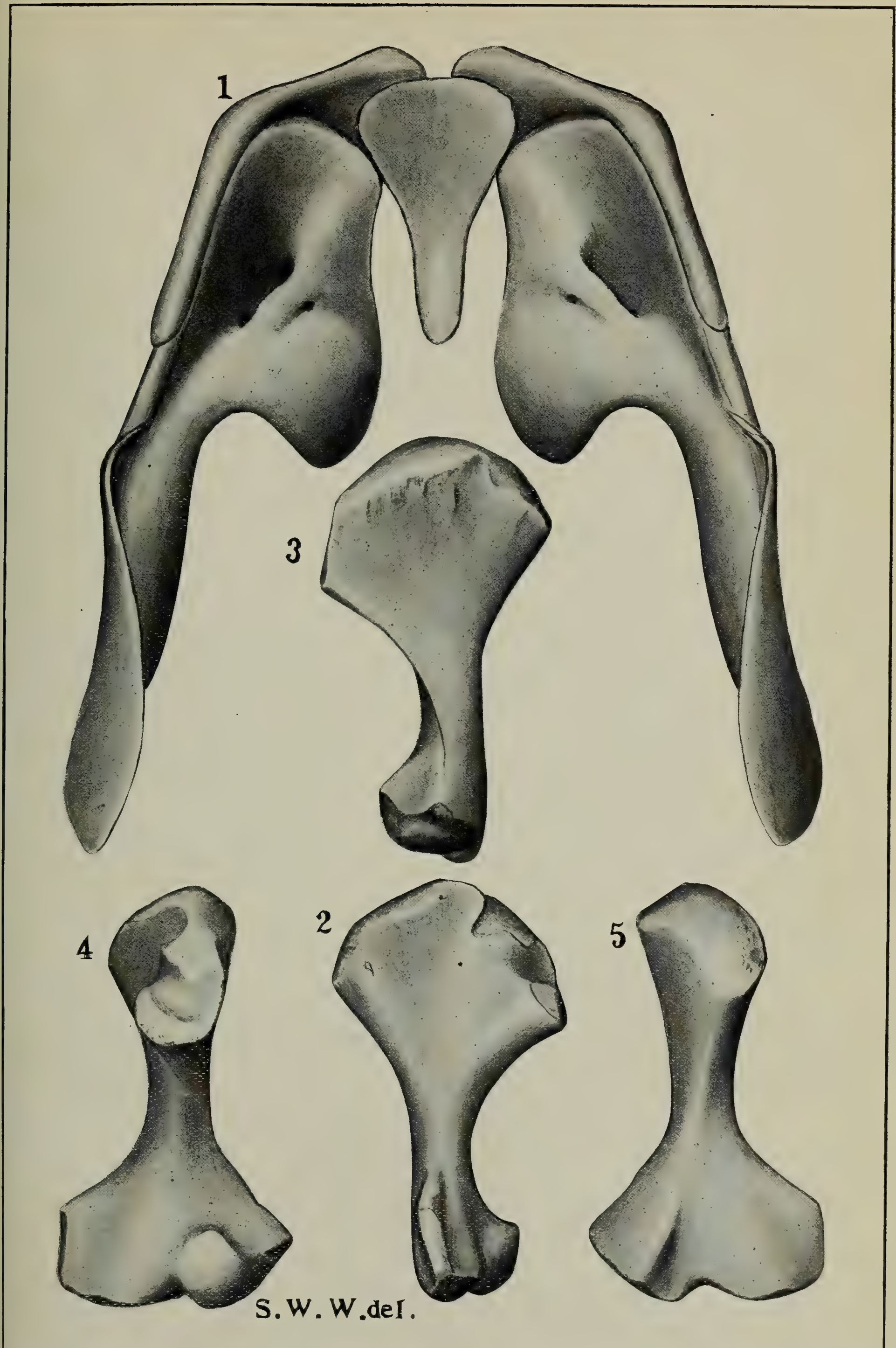

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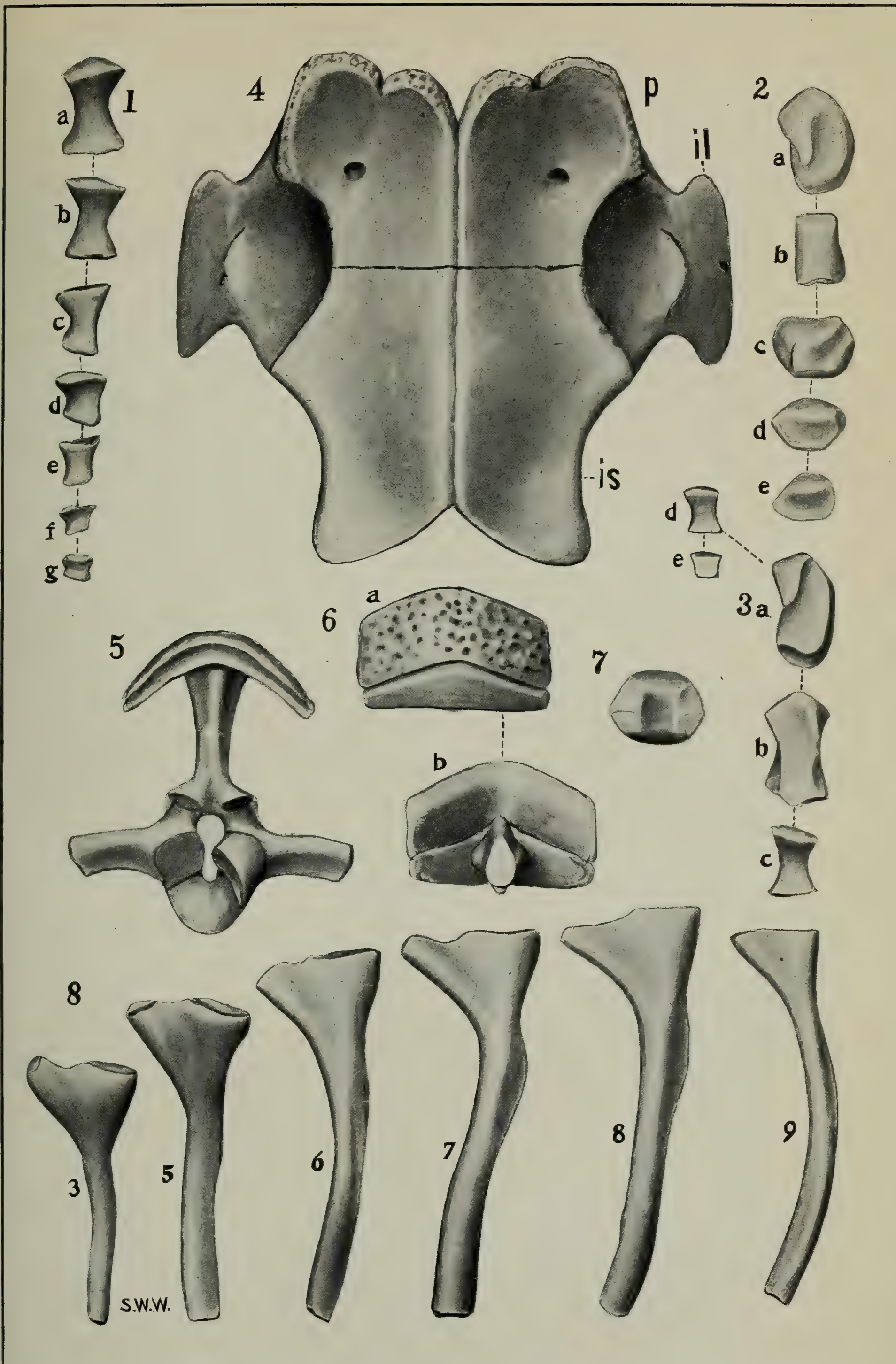

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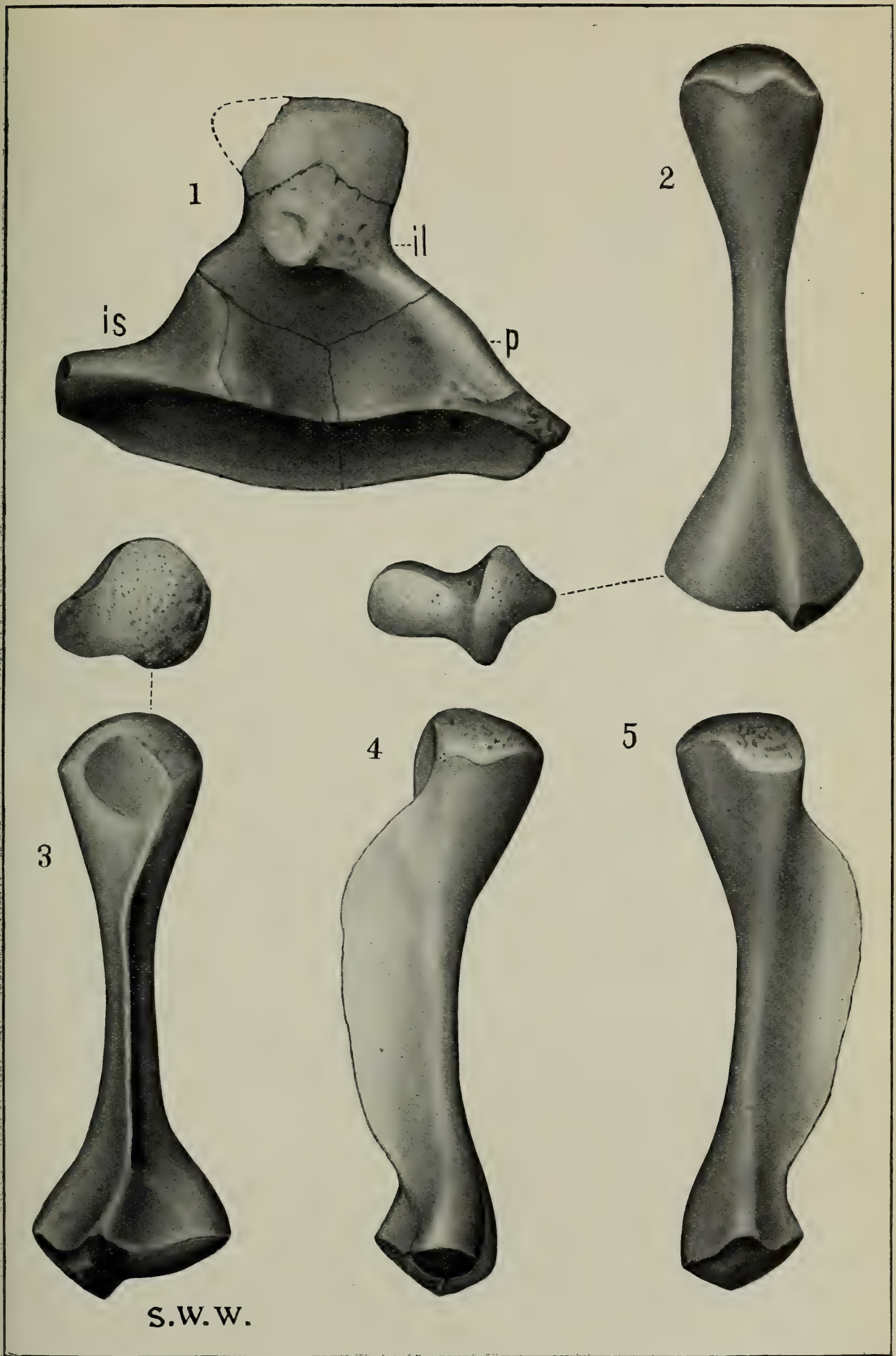

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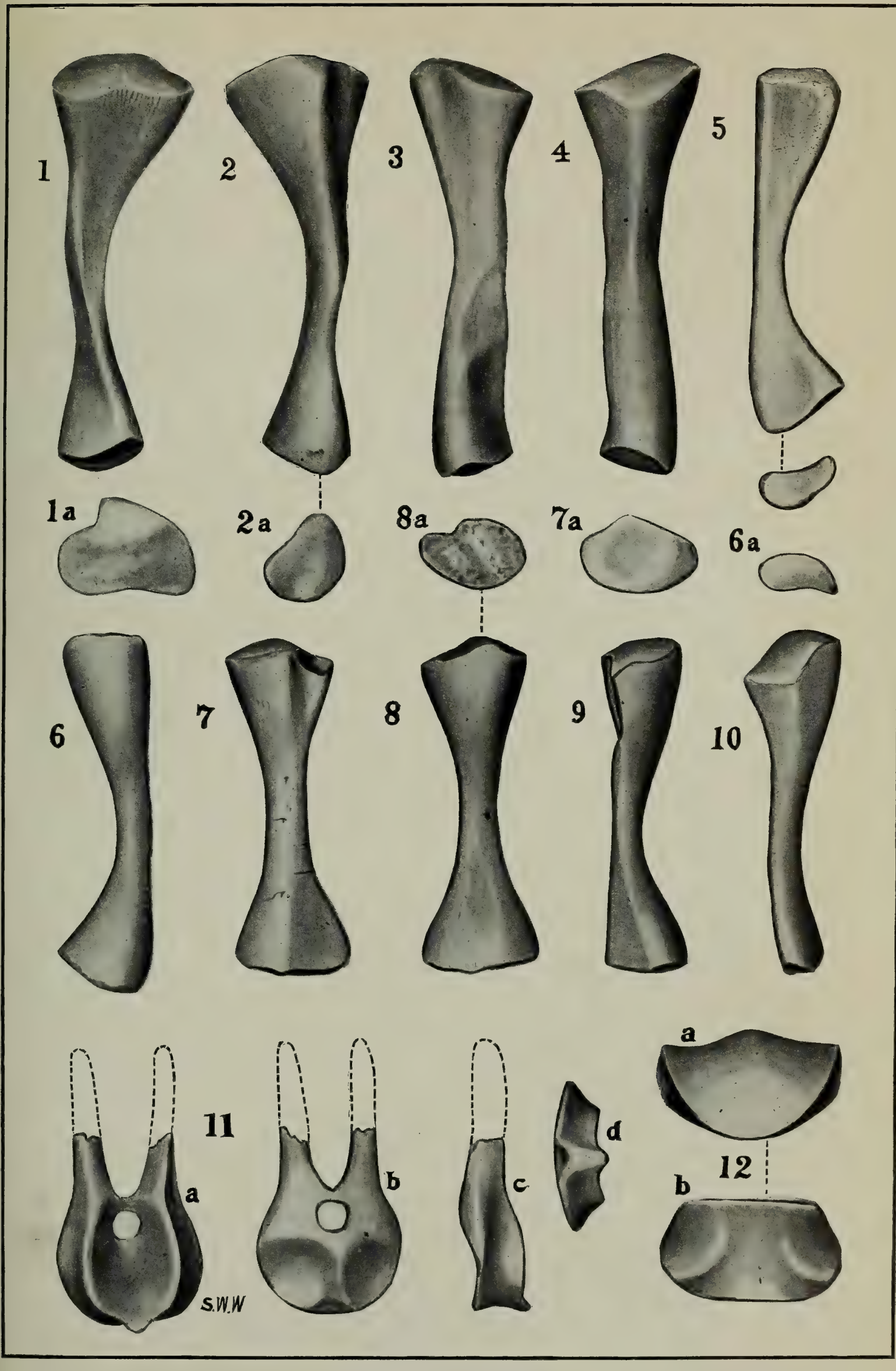

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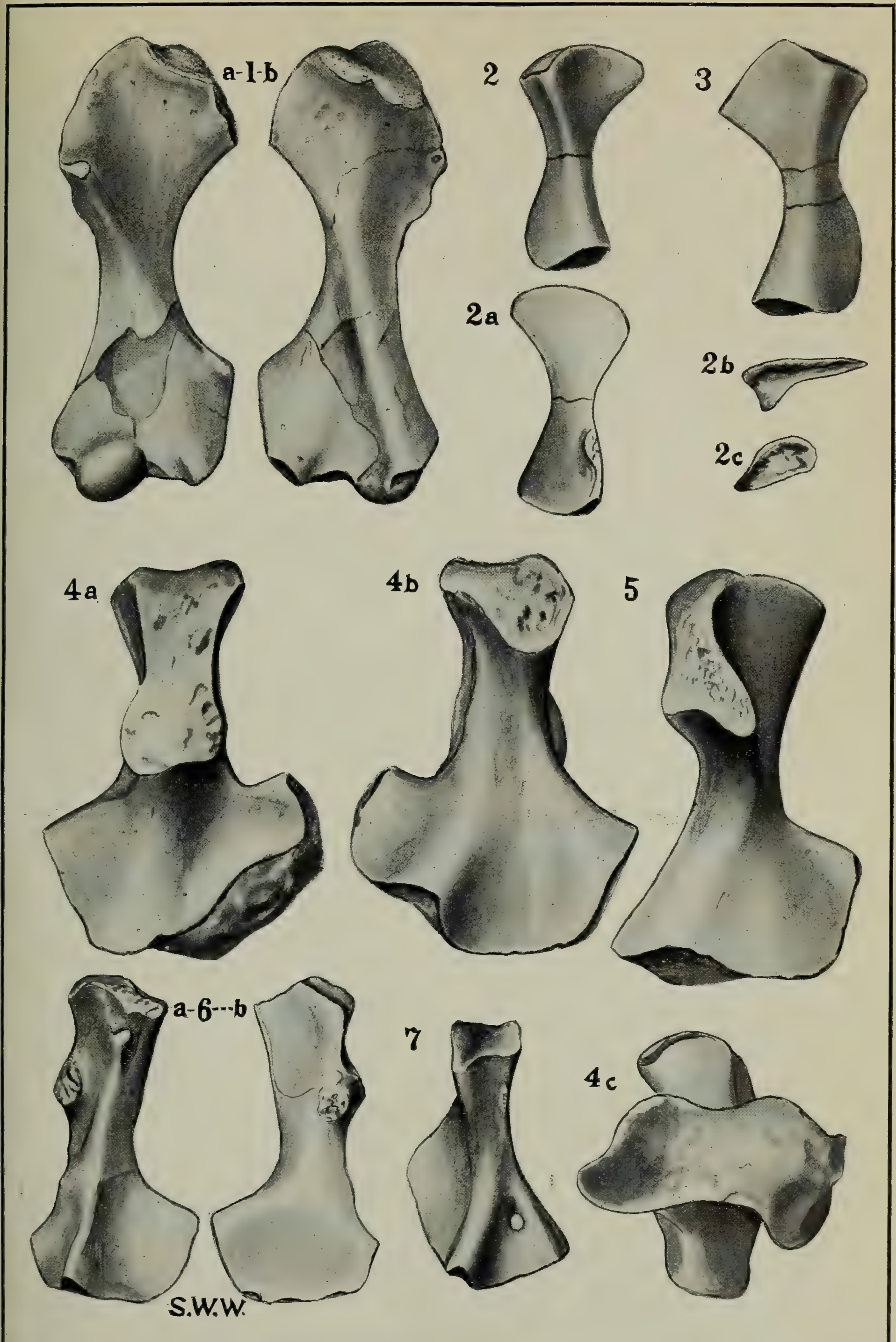

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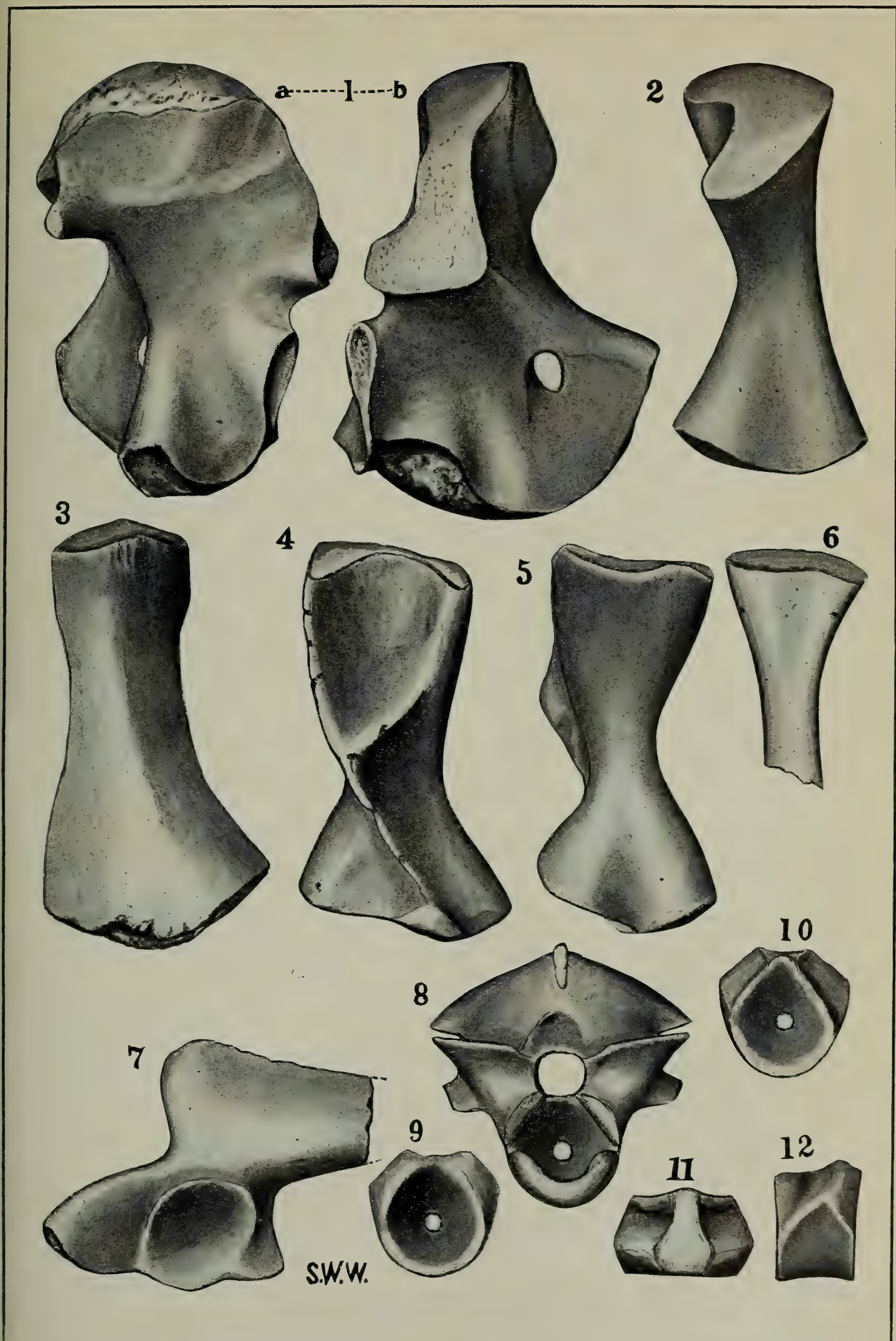

DESMOSPONDYLUS

CACOPS

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MIGRATION AND SHIFTING OF DEVONIAN FAUNAS[1]

BY HENRY S. WILLIAMS

(Presented in abstract before the Paleontological Society Dec. 31, 1909)

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The Hypotheses of Recurrence and shifting Faunas stated

In 1881 I presented before the American Association for the Advancement of Science the first definite announcement of the hypothesis of recurrent faunas, applying it to the fauna of the Marcellus, Genesee, and Ithaca black shales of new York, which I then conceived to be represented

[1] Manuscript received by the Secretary of the Geological Society April 23, 1910.

by the continuous fauna of the black shales of Ohio, Indiana, Kentucky, and Tennessee; and also, in the same paper, the hypothesis of shifting of faunas was applied to the Hamilton and Chemung faunas of central New York.[2] Since that time a large amount of evidence has been accumulated confirming these hypotheses. These hypotheses are intimately correlated. Recurrence or the departure of a fauna, its replacement by another, and its final reappearance in the same section at a higher level become the facts on which the hypothesis of shifting of the faunas is based; and the assumption of continuance and shifting of a fauna without losing its characteristics appears to be the only satisfactory explanation of its recurrence.

Facts on which the Hypotheses rest

The following facts explained by these hypotheses are among the more important which have come to light in the course of my studies.

CATSKILL SEDIMENTATION

This was shown to be thicker and to start lower down in the geological column in eastern New York than in middle and western New York. In eastern New York it began while the Hamilton marine fauna was still present and cut it off, bringing in estuarian conditions with a brackish water and land fauna and flora. In central New York no Catskill sedimentation is present until after the arrival of the Chemung fauna, and in western New York no trace of the Catskill type of sediments appears till after the close of the Devonian. These facts are direct evidence of shifting of the environmental conditions of the edge of the continent westward as the deposits of the middle and upper Devonian were being laid down. With this shifting westward of the off-shore conditions of the sea there went on a corresponding shifting of several faunas that were adjusted to each phase of those conditions.[3]

REVERSAL OF ORDER IN SUCCESSION OF FAUNAS

The appearance of the dominant species of the general fauna in reversed order of succession at the close of a fossiliferous zone.

The cases of *Spirifer lævis* in the Ithaca zone and of the frequent appearance of Leiorhynchus at the opening and close of a fossiliferous zone were among the earliest observed facts suggesting an actual shifting

[2] Proceedings of the American Association for the Advancement of Science, vol. xxx, p. 186, etc.

[3] "On the classification of the upper Devonian." Proceedings of the American Association for the Advancement of Science, vol. xxxiv, 1885, p. 222.

of the body of a fauna entering the area in one order of succession and departing in the reverse order.

In the Ithaca section there occurs at the base of the fossiliferous zone of the Ithaca member a bed containing abundance of *Spirifer* (*Reticularia*) *lævis.* The discovery of the same species at the top of the fossiliferous zone, as the normal Ithaca fauna become sparse, gave the first suggestion that the faunas were moving or shifting, the Reticularia zone marking the first trace of the fauna to enter and the last to leave the area. Confirmatory evidence was found in the order of succession of the dominant species of the Ithaca fauna. These facts were reported in 1883.[4]

The study of the mode of occurrence of Leiorhynchus still further drew attention to the definite order in which a series of species came in and went out of any given area. The species of the genus were generally found abundantly at the base or at the top of fossiliferous zones rich in brachiopods, in the midst of which Leiorhynchus was rare.[5]

RECURRENT HAMILTON FAUNA

The occurrence in a single or few strata of several representatives of an earlier fauna long after the formation to which they are normal has ceased.

Slight traces of this fact were observed in the first survey of the Devonian section passing through Ithaca,[6] and the fauna numbered 14 N (page 15) was called a "recurrent Hamilton fauna" because of the appearance there of such species as *Spirifer fimbriata, Sp. augusta, Pleurotomaria capillaria,* and others; and higher up, in the midst of the Chemung section, at Chemung narrows, *Tropidoleptus carinatus* and *Cypricardella bellistriata, Phacops rana* and *Dalmanites calliteles* were found.

The discovery of such traces of an earlier fauna led to further search, and as the evidence accumulated an elaboration and definite formulation of the theory of recurrence of faunas was made, which has been set forth in several papers, and is illustrated in detail in the folio of the Watkins Glen-Catatonk quadrangles, constituting folio number 169 of the U. S. Geological Survey.

ALTERNATE APPEARANCE OF DIVERSE FOSSILIFEROUS ZONES

The facts there brought out are substantially as follows:

There are exhibited in the sections mapped for the quadrangles *two*

[4] Bulletin 3, U. S. Geological Survey, p. 20, and Proceedings of the American Association for the Advancement of Science, vol. xxxiv, 1885, p. 222, etc.

[5] See Bulletin 3, U. S. Geological Survey, 1883, pp. 16 and 17,

[6] Reported in 1883, Bulletin 3, U. S. Geological Survey,

series of fossiliferous zones, the separate zones of the two series alternating in succession.

The zones of one series *dominate* the western sections of the area, and thus thin out or disappear on tracing them eastward. The zones of the second series dominate the eastern sections, and particularly the whole eastern New York sections, but thin out westward, and in some cases are entirely wanting in sections west of the Watkins Glen quadrangle.

The first set of faunal zones includes the faunas of the Genesee shale, the Portage formation, and the several divisions of the Chemung formation.

The second set of zones includes the Hamilton fauna, proper and recurrent representatives of that fauna, which I have named the *Paracyclas lirata* zone; the *Spirifer mesistrialis* zone; the *Leiorhynchus globuliformis,* or Kattel Hill zone (representing the typical Ithaca group of Hall at its typical sections at Ithaca); and the first, second, and third recurrent Tropidoleptus faunas, which I have called the Van Etten, the Owego, and the Swartwood Tropidoleptus zones.

All of these several fossiliferous zones of the second set become decidedly thin on passing westward across the region.

The Ithaca fauna is occasionally detected west of the Watkins Glen quadrangle, but is confined to less than 100 feet at Watkins, is recognized for 300 feet at Ithaca, and ranges through at least 600 feet along Tioughnioga River.

Only a slight trace of the Paracyclas zone is seen as far west as Ithaca, but is well expressed in the sections on the east side of the area.

The Van Etten, Owego, and Swartwood Tropidoleptus zones appear in thin tongues of strata as far west as the Waverly quadrangle and are seen in occasional traces as far west as the Elmira quadrangle, and when followed eastward appear to blend together as a modified Hamilton fauna, sparsely appearing in the strata up to the arrival of the Catskill type of sedimentation.

LIMITED RANGE OF RECURRENT SPECIES

Where the Hamilton recurrent zones are seen in sharpest exprssion the recurrent species range through only a foot or a few feet of strata, hold in abundance four or five characteristic Hamilton species, such as *Tropidoleptus carinatus, Cypricardella bellistriata, Rhipidomella vanuxemi, Spirifer marcyi* and *Delthyris mesicostalis,* cf. *D. Consobrinus,* and others, and the Owego and Swartwood zones appear in the midst of a characteristic Chemung fauna present both above and below each recurrent zone.

In the Owego recurrent zone both *Phacops rana* and *Dalmanites calliteles* occur.

The Van Etten recurrent zone lies entirely below the range of *Spirifer disjunctus* and other associated species of the Chemung formation.

On following the sections eastward from the Waverly quadrangle the species of the Chemung fauna become scarce, and east of the Chenango River very few species of the typical Chemung fauna have been detected, although they are still abundant in the Chemung rocks to the southeastward and southward across Pennsylvania, Maryland, and Virginia.

Interpretation of the Facts

SHIFTING OF FAUNAS

These facts have been interpreted as evidence not only of a general shifting of faunas coincident with a rising of the land along the eastern edge of the present continent, but of oscillation of conditions and alternate occupation of the area by two sets of faunas coming from opposite directions and temporarily living in abundance in the area of central New York.

LITHOLOGIC CHANGES NOT SUFFICIENT TO ACCOUNT FOR DIFFERENCES IN FAUNAS

The lithologic changes in the sediments containing the different faunas are not sufficient to account for the change in fauna. In quite a number of sections there is no appreciable difference in lithologic constitution between the strata which for 100 feet thickness have been filled with characteristic Chemung species and the immediately following thin zone of a foot or two, containing scarcely a trace of the Chemung species, but holding in great number species which if found by themselves would be undisputed evidence of the Hamilton formation.

DIFFERENCE IN OCEAN WATERS PRESUMED

It becomes necessary therefore to suppose that the controlling cause determining the presence of one or other fauna is not the character of the bottom on which the sediments which preserved the fauna were laid. We are thus led to conclude that the character of the ocean water has determined the shifting or migration of the faunas. The conditions to which the faunas were adjusted were evidently those of depth, salinity, or temperature of the waters in which the species lived; and their change of habitation was occasioned by change in the direction, path, or extent of flow of the oceanic currents.

This leads us to consider the general principles of migration, and in particular those which affect marine organisms.

Migration of Species and Shifting of Faunas contrasted

Migration as commonly applied in natural history means the movement of large numbers of the same species from one place to another in a general definite direction at more or less regular periodic times. So birds migrate northward with the advance of warm weather; some fish migrate from sea to rivers in breeding seasons; pigeons fly eastward or westward in great flocks; grasshoppers invade a rich country, devouring the vegetation in their path, or lemming migrate in great hordes from mountain to lowlands.

The term in these cases has to do with movements of one kind of animal in relation to the comparatively fixed range of feeding ground for the remainder of the fauna inhabiting the areas concerned. The term is rarely applied to the slower movement of the whole body of animals of a fauna, coincident with great changes of climate such as the advance of the glacial cover over the northern parts of Europe or America produced during the Glacial age, or the advance of an Asiatic fauna across the Bering Straits and down the west coast of North America at some Pleistocene time, when an ice-bridge furnished means of communication by land from one continent to the other. Perhaps there is no impropriety in extending the application of the term migration to these latter cases in which the whole fauna and flora of a region are affected instead of a single or a few species, and in which the change of position of habitat is slow and spread over a great period of time instead of being coincident with annual change of seasons. The term may equally well be applied to movements in the seas and movements on the lands.

There is, however, one reason for choosing a separate name for the movements of the latter kind to distinguish them from typical migration: In the first class of cases the migration is voluntary and is performed by those organisms which have the power of more or less rapid locomotion. They may be said to do the migrating themselves. In the second case the movements are involuntary and the movement is forced on all the living organisms of the region. The change in position may be supposed to take place by the contraction on one side of an area of the conditions of possible existence for the species and the extension on the other side of favorable conditions of environment. The movements extend over many generations of life, so that relatively sedentary species may gradually adjust their *locus habitans* in the given direction of motion. To this latter process of migration I have been accustomed to apply the term "shifting of faunas."

Migration of species is in its typical sense an expression of the ability of some organisms to appreciate slight favorable changes in the conditions of environment and to take advantage of the better conditions during the lifetime of an individual. Shifting of faunas is an expression of the felt necessity, for the perpetuation of the race, of certain conditions of environment, resulting in the dying out of the whole fauna in the areas from which the favorable conditions have been removed and the spread of the fauna into new areas into which the favorable conditions have been shifted.

Shifting of faunas is an expression of the inability of any species of the fauna to survive under the changed conditions of environment which have overwhelmed them in their original habitat, but of an ability on the part of all those which migrate to follow the favorable conditions as they shift from one area to another.

Changed Environment Cause of both Migration and Shifting

In both typical migration of species and shifting of faunas, change in the environmental conditions of life constitutes the stimulus inducing change of habitat on the part of the organisms, and the movement of the organisms is a direct response to the stimulus. Those organisms in the first case which migrate show their greater vitality, compared with their neighbors who stay at home; while those who stay at home show the greater power of endurance and of organic adjustment to a wider range of environmental conditions than do those which migrate.

Close Adjustment of Species of a shifting Fauna

In the case of the shifting fauna, those species which endure without change of characters exhibit an acquired closeness of adjustment to some particular combination of environmental conditions which they are forced to follow or die and suffer annihilation. The evidence of their endurance is indicated by their return and reoccupation of the same area at a later geological stage when, by their reappearance, the original condition of environment is shown to have recurred.

Evidence of Migration

In the case of living organisms evidence of migration is found in the actual presence of the species at one time in a region at a considerable distance from its ordinary *locus habitans;* and in some cases the species may be seen in the process of migration, as, for instance, the temporary alighting, in fatigued condition, of flocks of northern land birds on Bermuda Island on their migration southward.

In the case of fossil species the shifting of a fauna is recognized by the presence in a stratum of rocks of a number of species representing an earlier fauna surrounded by a different and, dominantly, later set of species.

Recurrence

The fauna is then said to *recur,* and it is the recurrence of the fauna which forms the basis for the inference that the fauna has shifted its *locus habitans* during the period of time represented by the sedimentary deposits separating the formation in which the fauna is dominant from the zone in the higher formation in which the recurrent species are found.

Theoretical Problems involved

This hypothesis of shifting of place and recurrence in time of a fauna involves certain conceptions as to the nature of species and the laws of evolution which it is important to consider.

Evidence of faunal Continuity

To establish evidence of motion in migration, as in any other kind of motion, it is all important to know that the body or bodies to which the motion is ascribed is continuously the same.

In the Devonian case the moving body is a fauna. Not only is it necessary to establish identity of the species in the recurrent zones with those of the initial zones, but it is essential to show that the faunas as a whole are the same. To put this in another mode of statement, we must establish the fact that not only the individual species have retained their specific characters, but the further fact that the equilibrium of adjustment to each other in the faunal community has not been changed, in order to prove that a supposed recurrent fauna is actually the direct successor of a fauna represented in the rocks at a lower horizon.

Rare and dominant Species

This has led to the distinction between rare and dominant species. Only as the comparative frequency of the species in the faunal combination is maintained can we be sure that we are not considering an accidentally accumulated sample of a general fauna instead of the successive appearance of a special fauna.

The presence of an occasional associated species belonging normally to the fauna of the formation in which the recurrent zone appears is not antagonistic to the hypothesis, because the hypothesis proposes an invading of the territory already occupied by a normal fauna; and in case the currents or other causes which brought about the shifting of the fauna were not so completely different as to annihilate all evidence of the fauna previously occupying the ground, some few species might be supposed to hold over. Hence it is only necessary to find an abrupt change of the majority of species to make the induction that the faunas have shifted their habitats.

Magna Faunas and local special Faunas

The theory involves the further conception of grand general faunas or magna-faunas which have their center of habitat and distribution in permanent oceanic basins, as distinguished from the local, special and (in geological strata) temporarily expressed faunas, such as we are accustomed to associate with individual geologic formations.

In the case before us two such magna faunas are in evidence, one of which in its dominant characteristics is traced westward into Iowa, Idaho, and Arizona and up the Mackenzie River valley to the north, and across the polar regions to Russia and northern Europe. The other is traced eastward and southward into central and southern Europe, and also appears dominantly in South America.

In a case of recurrence in which there has been continuous sedimentation it is practically impossible to distribute all the species according to their source of origin. I have found it possible, however, to distinguish a few species as undoubtedly derived from a source different from that of the prevailing fauna characterizing the beds both below and above the recurrent zones.

Fixed and fluctuating Characters

It is only by close examination and comparison of the fossils themselves that identity of species or identity of faunas can be established.

The fixed characters are not only those characters by which one species is distinguished from another, but they include others of generic, ordinal, and even class rank, which may be of immense age in the race and mark no special narrow stage of its history.

It is a question of interpretation whether each particular phase of expression of fluctuating characters is a matter of time or of environment.

I have reached the conclusion that it is those species whose characters have the greater degree of normal and persistent fluctuation which migrate and follow the shifting conditions of environment, and their life period is correspondingly longer.

On the other hand, species whose plasticity of characters is narrow are more closely adjusted to their environment, are local in their range of habitat, and are temporary in their geologic life period.

Interpreting the facts on this basis, it is the phases of continuously fluctuating characters in species of wide geographic distribution and of long geologic range which furnish the most satisfactory evidence of temporary stages in the life history of faunas.

Difficulties in establishing Evidence of strict Contemporaneity

Another question of interpretation arises when we attempt to reconstruct the physical condition of the environment at successive stages of time.

In a single vertical section we have positive evidence of succession in time. If we were sure that no recurrence of the same fauna could take place, we could correlate two vertical sections strictly upon the fauna contained in the strata—on the hypothesis that the single fauna existed but once, and when it ceased in a given section its whole life period had been expressed. But the facts show us that this is not the case in nature. In geological times, as in the present, we know that many distinct faunas are living on the face of the earth at the same time, even for very similar conditions of environment. It becomes, therefore, a very complex matter to establish the fact of contemporaneity or to correlate two sections in which the order of faunas and the character of the sediments differ, which is generally the case for any two sections separated by 50 miles from each other, although on stratigraphic evidence they may be properly interpreted as covering the same interval of time.

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PERSISTENCE OF FLUCTUATING VARIATIONS AS ILLUSTRATED BY THE FOSSIL GENUS RHIPIDOMELLA[1]

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(*Presented in abstract before the Paleontological Society Dec. 31, 1909*)

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Introduction

The following paper is the result of investigations which were begun several years ago, under the inspiration of Huxley's prophecy that paleontology, when properly interrogated, would reveal to us the true laws of evolution. I have at last succeeded in getting together a long series of samples of a single race inhabiting successively the same region; have subjected them to minute measurement, and by reducing their morphologic characters to mathematical terms have enabled them to speak for themselves regarding at least one of the essential laws of evolution, the law of fluctuating variation.

Inadequacy of vague descriptive Terms

One of the greatest difficulties met with in making such an investigation is the practice of using extremely vague and elastic terms in describing the specific characters of fossil organisms. Generic characters are in many cases made more definite by the fact that the diagnostic characters are either present or absent or the repeated parts are found in definite numbers; but in distinguishing species the use of such terms as short, long, broad, thick, deep, high, oval, ovate, oblong, etcetera, which are very commonly applied to both the gross morphology and the description of each distinguishable part of a fossil, stand directly in the way of all progress in the discovery of the minute steps by which modification of form is accomplished in evolution.

Application of biometric Method

My paper is therefore not only a statement of some facts, but an application of the biometric method to the interpretation of fossils.

The genus *Rhipidomella* Oehlert was selected for first application of the method, almost at random among a number of similar series, chiefly because as a morphologic form it can be easily and certainly distinguished from all associated genera, and, further, because it offers clear and distinct characters for measurement.

Prerequisites to the Study of Evolution of Fossils

Before it is possible to interpret the laws of evolution from a geological series of specimens so that the results can be regarded as scientifically established, a rigid control of the conditions of selecting the samples is essential. The samples must all be of one genus; the fauna in which they occur must be unchanged and continuous; the length of time and the change of environmental conditions must be sufficient to furnish the opportunity for evolutional modification; the effects of geographic distribution and of artificial selection of the specimens must be eliminated and some mode of mathematical expression of the facts must be devised which will not only be exact, but will eliminate the changes of dimension incident to ontogenetic growth of the individual.

Faunal Continuity

In order to obtain a continuous series of samples of the same genus, running through a period of geologic time long enough to satisfy the conditions for the evolution of new species, it was necessary to establish faunal continuity, for the reason that where there is a faunal break of continuity in succession there can be no certainty that the specific representatives of the same genus in the two faunas have the same origin. They may have had widely different origin and represent evolutional races whose ancestry had been distinct for long periods of preceding time.

Environmental Change sufficient to permit evolutional Modification

Again, in order to establish the fact that the genus had suffered a sufficient amount of environmental change to give it an occasion for evolutional modification, it seemed necessary to trace the genus through more than a single stage of its life history, for the reason that any morphologic differences expressed by a genus under a single set of environmental conditions can be interpreted only as fluctuating variations within the limits of specific characters and may have nothing to do with evolutional modifications.

Effect of geographic Distribution

In order to be sure that geographic distribution did not enter in to complicate the evidence, it was necessary to collect the samples from a series of successive beds within a limited area within the confines of the same geologic basin.

Artificial selection of Evidence

Further to insure that no artificial selection of evidence take place, uniform conditions of collecting the evidence and a very thorough search, and the subjecting of every trace of the evidence to examination were necessary conditions.

Biometric Method

And, finally, because of the elastic and indefinite nature of descriptive terms applied to form, it was necessary to reduce the characters under examination to mathematical terms, so that they could be accurately stated and compared. I made all measurements myself, and with the same instruments, in order that whatever personal equation might enter into the statistics the errors would be reduced to a minimum by being uniform for all the statistics.

Location and geologic Horizon of Specimens

It has taken a number of years to satisfy all these conditions (I started the investigation in 1881), and in August last I began, for the first time, to make the measurements, the results of which I now have to report.

The geological sections from which the specimens were obtained are all within an area in central New York within a radius of 50 miles from Ithaca as a center.

Stratigraphically, the zones range from the middle of the Hamilton formation, through the Genesee, Tully, Portage, and to the top of the Cayuta member of the Chemung formations, presenting a total thickness of approximately 2,300 feet, which is at least 1/100 part of the thickness of the whole sedimentary beds of the earth's crust from which distinct evidence of organisms has been obtained. In time, according to various estimates, this represents from 270,000 to over 1,000,000 years.

Geologic Section

THE ZONES AND INTERVALS

The samples of the genus come from five distinct zones in the following order:

Chemung	Swartwood zone : Interval of 400 feet. Owego zone : Interval of 400 feet.
Portage	Van Etten zone : Interval of 900 feet. Ithaca zone : Interval of 600 feet.
Hamilton	Hamilton zone.

HAMILTON ZONE

In the Hamilton formation of Cayuga Lake the genus Rhipidomella ranges through the upper 300 feet of the rocks (according to Professor Cleland's careful elaboration of the facts, given in Bulletin 206 of the United States Geological Survey), and for the upper 200 feet it is a common species in almost every fossiliferous zone. The samples subjected to exact measurement were obtained from the middle of this zone, perhaps 200 feet below the Tully. The whole of the Tully limestone, the Genesee black shale, and the Sherburne member of the Portage, each with a distinctive fauna, intervened between the first and second zone from which our specimens were obtained.

ITHACA ZONE

The second set of samples of the recurrence of Rhipidomella were obtained in a single layer in Buttermilk Creek south of Ithaca by Dr. E. M. Kindle. They lie below the main fossiliferous zone of the Ithaca member of the Portage formation, fully 600 feet above the first horizon of the Rhipidomellas of the Hamilton. About 900 feet of strata, holding the typical Ithaca fauna of the upper or Enfield member of the Portage, intervene between the Ithaca and Van Etten zones.

VAN ETTEN ZONE

The zone in which the next sample of the genus Rhipidomella appears is about 900 feet above the Ithaca zone in (what has been called and mapped in the Watkins Glen-Catatonk folio) the first recurrent Tropidoleptus zone. This zone is typically represented in the section at Van Etten and contains Rhipidomella in 17 localities in the area examined. This zone is in the upper part of the Enfield member of the Portage, below the first appearance of the Chemung fauna in the section.

OWEGO ZONE

Four hundred feet above the Van Etten zone the Owego, or second recurrent Tropidoleptus, zone appears. This zone is about 200 feet above the first appearance of the Chemung fauna and 400 feet below the top of the Cayuta member of the Chemung.

SWARTWOOD ZONE

This zone is the third recurrent Tropidoleptus zone of the folio and lies at the top of the Cayuta member. In this particular area no *Spirifer disjunctus* has been discovered above the Swartwood zone.

Recurrent Tropidoleptus Fauna in the Watkins Glen-Catatonk Folio

Careful search has been made of every fossiliferous section over the 8 15-minute topographic quadrangles making up the area of the Watkins Glen-Catatonk folio, and in 34 localities samples of Rhipidomella have been obtained, all in association with other species representing the general recurrent Tropidoleptus fauna. In some cases only two or three specimens are in evidence; in the majority of cases, however, from 10 to 12 or more good specimens for measurement are in evidence.

Distribution of Sample Sets by Zones

The number of different sample sets is as follows for the several zones:

Ithaca	2
Van Etten	17
Owego	6
Swartwood	9

For the Hamilton zone a large collection of specimens obtained by H. H. Smith from the shore of Cayuga Lake furnishes the specimens for the series here recorded. The figures given by Hall of the type specimens of the Hamilton species of New York State were also measured for comparison. In all there are 35 sets of samples, each set from a particular stratum of rock at a single locality. Each of the sets except that from the Hamilton is from a zone of rock above the Hamilton, containing Tropidoleptus and other characteristic Hamilton fossils, but at such a position in the rock section that its exact stratigraphic position is fully established. The association of species in each case is sufficiently large and distinctive to establish the recurrent nature of the fauna.

Between the zones mentioned no trace of the genus Rhipidomella has been found anywhere in the area studied.

All the specimens gathered were examined, and all those sufficiently perfect to furnish the measurements needed were tabulated.

Number of Specimens measured

The total number of specimens measured was nearly 300. Those furnishing both length and width were 277, distributed by zones as follows:

	Specimens
Hamilton	20
Ithaca	24
Van Etten	115
Owego	40
Swartwood	78

Measurements and Ratio Indexes

Each one of these specimens was measured by vernier calipers reading to 1/10 of a millimeter, for (*a*) its length from point of beak to middle of front margin furnishing index L, and (*b*) its width across from side to side at place of greatest width giving the index W.

The ratio between length and width obtained by reducing the value of index W to its percentage of the value of index L formed the ratio index R^1.

One hundred and forty-two specimens of pedicle valves showing the interior and the muscular scar were measured.

These were from the zones as follows:

	Specimens
Hamilton	12
Ithaca	0
Van Etten	48
Owego	26
Swartwood	56

For each of these the values of the length (index L^1) and the width (index W^1) of the muscular scar were obtained, and then the measures were also reduced to the percentage ratio of width to length to obtain the index ratio R^3.

The index R^2 was obtained by comparing the length of the muscular scar with the length of the shell; this ratio reduced to percentage was ratio index R^2.

Reasons for Selection of Rhipidomella for Study

A word of explanation may be here offered as to the reasons for selecting the genus Rhipidomella and the particular dimensions for measurement. Rhipidomella was chosen because it offered a number of distinct morphologic characters which at a glance could be seen to fluctuate, as well as others which seemed to be repeated with great precision and were alike for all the specimens. The specimens were also well preserved or else left clear impressions when the shell was dissolved from the rock.

There was no other genus represented in these rocks so closely related to Rhipidomella as to furnish any doubt as to the proper reference of the specimens to the genus. Schizophoria, in young specimens, might possibly be confused with young specimens of Rhipidomella if only the exterior were in evidence; but no case arose in which the generic relations were not evident. Also Rhipidomella is fairly well represented in number of specimens for the majority of the faunules showing the recurrent Tropidoleptus fauna.

The particular characters and dimensions chosen for measurement were selected because of their fitness to furnish accurate measurements and because they well represent the general and particular fluctuating characters of the shells.

Form of Shell, Ratio Index R^1

It was observed that the various described species of the genus differ most conspicuously in the shape of the shell. While this shape is made up of a large number of details, differences in any one of them appear to affect the proportion between width and length, and for this reason these dimensions were chosen for measurement. By taking these two diameters and reducing them to a percentage scale, a ratio index was obtained which expresses by a single number the particular form fluctuation of each specimen on a common scale, whatever the size of the shell. This ratio index R^1 furnishes, therefore, not only a mathematical expression for the shape of an individual shell, but it is a means by which differences in shape can be readily compared, both in amount and direction of fluctuation, with mathematical precision.

Muscular Scar of Pedicle Valve

The other character chosen for measurement was the muscular scar of the pedicle valve. This is a conspicuous, peculiar, and fluctuating character of the genus, and as it is well defined on good specimens and molds of the interior, it furnishes a valuable second character for precise study.

The muscular scar differs considerably in form and size in the various described species of the genus, and these differences, of whatever kind, have more or less direct effect on the proportion between width and length. Hence each scar was measured for length and width, and from the two measurements the value of index R^3 was obtained, which expresses in a single mathematical term the percentage ratio between the width and length of the scar.

Proportionate Rate of Growth of Parts

A third relation, also expressing differences in the rate, the proportionate rate in different parts, and the direction of growth, was obtained by estimating the percentage ratio between the length of the muscular scar and the length of the shell; this percentage gave the value of index R^2 for the several shells.

Ratio Indexes R^1, R^2, R^3

METHOD OF PROCEDURE

Thus were obtained three ratio indexes, represented by the values of R^1, R^2, R^3. The values for each index should be alike for any two shells presenting no variational differences; and the difference in value of the indexes for different specimens expresses, on a common scale, the kind and degree of difference in form, directly in three ways and indirectly in a large number of ways not easily describable otherwise. If the shell changed its form on passing from young to adult state, comparison of the values of their indexes for small and for large specimens will show it. Hence the law of ontogenic growth can be distinguished from and compared with the law of the phylogenic modification by comparison of these ratio indexes.

Although I caught something of the drift of the evidence as I was preparing the statistics, I deliberately put the specimens away in drawers, after all the measurements had been recorded, and used only the recorded value of the three ratio indexes, without attempting to interpret them into characters, in estimating the following results.

RESULTS

Explanation of the ratio indexes.—The chief results are expressed in the mathematical values of the three ratio indexes R^1, R^2, R^3:

R^1 stands for the form of the shell;

R^2 stands for the proportionate size of the muscular scar in relation to the size of the pedicle valve;

R^3 stands for the form of the pedicle muscular scar.

The index L stands for size of shell expressed in millimeters;

L^1 stands for size of the muscular scar in millimeters.

1. *Size of shells—Values of index L.*—(*a*) The average length of 277 specimens from all zones is 19.1 millimeters.

(*b*) The mean of averages for the 35 separate faunules is 19.8 millimeters.

(*c*) Average length of the separate specimens of each zone by zones is, for 20 Hamilton specimens, 18.2 millimeters; for 24 Ithaca specimens, 17.5 millimeters; for 115 Van Etten specimens, 18.6 millimeters; for 40 Owego specimens, 20 millimeters; for 78 Swartwood specimens, 19.8 millimeters.

Uniformity in average size.—(*d*) This shows a remarkable uniformity in the average size of the specimens; the value of L varies from 17.5 to 20—that is, 2½ millimeters.

Here it should be noted that special directions were given to the collectors to make no selection in collecting specimens, but to gather specimens as far as practicable to represent the actual relation of abundance and rarity shown by the several species and the range in variation in size and other characters expressed by each species for each separate faunule.

Length of shell increases on passing upward.—(*e*) Examination of result (*c*) above shows that there is a slight increase in the average size of the shell on pasing upward. This is in harmony with another fact not brought out by the statistics. The thickness of the shells shows a decided increase on passing upward. In the Hamilton and Ithaca zones the shells are mainly frail and often crushed in fossilization. In the upper zones rarely are any specimens crushed, and there are frequent specimens showing thickening at the margin and strengthening of the processes about the hinge and bordering the muscular scars.

Size alone not significant of evolution.—(*f*) The size of the shell alone, however, can not be used as an index of evolution, because each shell has a differing size index for different stages of its own individual growth; and, secondly, because size of specimens of any particular faunule is determined partly by the stage in individual growth at which the specimen died, but chiefly by the *rate of motion* of the currents which selected the particular shells at the point of their fossilization.

2. *Size of muscular scar—Values of index R^2.*—(*2a*) The average of R^2 for 142 specimens for all zones is $R^2 = 64.1$.[2]

(*2b*) The average for the specimens of each zone by zones: For 12 Hamilton specimens is 60.7; for the Ithaca, no evidence, 0; for 48 Van Etten specimens is 64.8; for 26 Owego specimens is 63.2; for 56 Swartwood specimens is 64.7.

(*2c*) In order to catch more fully the ontogenic law of development of this character, it is necessary to note the fluctuation in value of the index R^2.

For the Hamilton set the amount of fluctuation is from 47 to 71 per cent = 24 per cent.

For the Van Etten set the amount of fluctuation is from 57 to 82 per cent = 25 per cent.

For the Owego set the amount of fluctuation is from 56 to 72 per cent = 16 per cent.

For the Swartwood set the amount of fluctuation is from 52 to 78 per cent = 26 per cent.

Phylogenic increase in size of muscular scar.—This shows a slight phylogenic increase in proportionate size of the muscular scar, both in the lower and higher limits, namely, from 47 to 52 and from 71 to 78.

Examining this character for one of the earlier representatives of the genus, namely, *Orthis hybrida* Hall of the Niagara, we find in the type figures the index $R^2 = 56$. Two characteristic Coal Measure forms at the other extreme of the evolutional history of the genus give $R^2 = 63.3$ (for *Orthis pecosi* Marcou) and $R^2 = 70$ (for *Orthis penniana* Derby); difference, 56-70 = 14 per cent. This shows that the phylogenic tendency is decidedly toward an increase in the length of the muscular scar with time, represented by 14 per cent between the Silurian and Carboniferous samples.

Fluctuating value of index R^2 for three type species of the Hamilton.—Again, if we examine the type specimens figured to represent the several Hamilton species, the fact appears that *Orthis leucosia* may normally vary in value of R^2 from 69.2 (figure 4*h*) to 83.9 (figure 4*i*), or 14.7 per

[2] The number 64.1, as the value of R^2, means that the muscular scar averages 64 and 1/10 per cent of the length of the shell, and so in all expressions of the value of R^2.

cent; that *Orthis penelope* may differ from 46.8 (figure 2*g*), 56.3 (figure 2*i*) to 61.6 (figure 2*h*), or 14.8 per cent, and that *Orthis vanuxemi* (figures 3*m* and 3*r*) may normally differ from 69.2 to 74.8, or 5.6 per cent.

Comparison between ontogenic fluctuation and phylogenic modification.—These statistics show a range in value of this index, for the Hamilton types alone, from 46.8 to 83.9, or 37 per cent, which exceeds in both extremes the extreme limit reached by any of the specimens measured in our series; it also exceeds the limit of fluctuation of this character expressed by the average value of R^2, as recorded by typical figured specimens of characteristic species from the early and latter ends of the life history of the genus.

To bring out this point more distinctly, we note the difference between the extremes in percentage values.

The extreme fluctuation in value of index R^2 between typical Niagara and typical Carboniferous forms is 14 per cent; for typical figured specimens of Hamilton species, 37; for typical specimens of the species *O. leucosia*, 14.7; for typical specimens of species *O. penelope*, 14.8; for typical specimens of species *O. vanuxemi*, 5.6; for measured specimens from a single Hamilton faunule, 24; for measured specimens from the Van Etten zone, 25; for measured specimens from the Owego zone, 16; for measured specimens of the Swartwood zone, 26.

But the total amount of change in the average value of index R^2 from the Hamilton to the Swartwood zone is only 4 per cent.

It seems evident from these statistics that the difference in value of the character R^2 is from 4 to 6 times greater for any set of specimens selected at any particular stage in the history of the genus than the difference in value shown by two samples separated by a period of time represented by the sedimentation of 2,300 feet of sediments in the passage from the Hamilton formation to the top of the typical Chemung.

This law of the persistence of fluctuating variation is equally well indicated by comparison of the evidence of fluctuations for each separate faunule.

3. *Shape of the shell—Values of index R^1.*—The statistics regarding the shape of the shell are found in the measurements of 275 specimens, representing 35 separate sample faunules, and from 5 distinct stratigraphic zones. The morphologic character involved is one of the most conspicuous as well as important of the characters used in specific diagnosis.

If the average of the values of the index R^1 of all the specimens of each zone is taken, the following results are found:

	Average.	Extremes of fluctuation.	Amount of fluctuation.
For 20 Hamilton specimens..................	111.9	104.5–118.2	13 7
21 Ithaca zone specimens................	108.1	99.2–125.5	26.3
115 Van Etten specimens..................	109.3	73.4–147.8	74.4
40 Owego specimens......................	105.6	91.0–119.5	28.5
79 Swartwood specimens.	108.2	91.3–137.3	46.0
Average for the whole set..............	108.2		

From these statistics it is evident that the amount of phylogenic modification of this character R^1 (105.6 to $111.9 = 6.3$ per cent) is extremely small in comparison with the ontogenic fluctuation (see last column in above table) for any one of the zones examined.[3]

Amount of ontogenic fluctuation great.—The amount of the ontogenic fluctuation is brought to light in another way by tabulating the differences in value of the index R^1 for each separate sample lot and computing the average for the whole 35 lots.

There are 35 lots of specimens, each lot from a single locality and faunule. The range of fluctuation in value of the index R^1 for each lot is shown by the following summary:

7 lots show no variation, because there is but a single specimen in evidence	0
6 lots show a range of fluctuation less than........................	10 per cent
6 lots show a range of fluctuation between...............	10 and 19
11 lots show a range of fluctuation between...............	20 and 29
1 lot shows a range of fluctuation between................	30 and 39
3 lots show a range of fluctuation between...............	40 and 49
1 lot shows a range of fluctuation of............................	58
The average amount of fluctuation in value of R^1 for the 35 lots is..	17

The fluctuation of this character expressed by the type figures of several described species is as follows:

	Amount of fluctuation.	Mean.
Orthis cyclas Hall..........................	110.8 – 117.1 = 6.3 per cent	113.9
Orthis idoneus.............................	107 – 113.8 = 6.8 per cent	110.4
Orthis leucosia	103.5 – 112 = 8.5 per cent	107.7
Orthis penelope............................	106.7 – 121 = 14.3 per cent	113.8
Orthis vanuxemi............................	107 – 111.8 = 4.8 per cent	109.4

and the total difference in form expressed in values of R^1 for these five Hamilton species, as above enumerated, based on measurement of the

[3] Phylogenic modification is the amount of morphologic change distinguishing the representatives of one stage from those of another following stage of its history; ontogenic fluctuation is the change in form expressed by different individuals of the same race living at one and the same time.

type figures, amounts to 103.5–121 = 18 per cent—that is, the extreme difference expressed by the type figures of the five species of the Hamilton is only 1 per cent greater than the average difference for each lot of the 35 lots of measured specimens.

Seventeen of the 35 sample lots collected in the field show a greater amount of difference in this character (index R^1) than the total amount of difference between the extreme examples of the type specimens of all the species of this genus described from the Hamilton for the New York area.

The difference between the mean values of index R^1 for the Hamilton type figures is only (107.7–113.9 =) 6.2, and 22 of the 35 samples show a wider fluctuation than 6.2.

Nevertheless, the greatest amount of difference between the average values of R^1 for the several zones, taken by zones, is (105.6–111.9 =) 6.3, and both extreme average values taken by zones are less by almost exactly 2 per cent than the actual extremes expressed by all the typical Hamilton species.

Phylogenic modification slight.—The statistics show a slight decrease in value of index R^1 on passing upward from the Hamilton to the upper Chemung zone, which fact is in harmony with the general phylogenic movement for the whole evolutional history of the race, as shown by comparing two Silurian species with two characteristic Carboniferous species:

	Value of Index R^1.	Average.
Orthis circulus of the Clinton	117.3	116.6
Orthis hybrida of the Niagara	116.0	
O. pecosi Marcou, Coal Measures	86.2	86.8
O. penniana Derby, Coal Measures	87.5	

showing a decrease of about 30 per cent on passing from the Silurian to the close of the Carboniferous (Pennsylvanian).

Phylogenic modification in same direction as ontogenic growth.—This phylogenic decrease in the value of index R^1 is also in harmony with the ontogenic law shown by comparing the young with the adult stage of a single specimen. The young forms are always broader than the adult, which would be expressed by higher percentage in the value of R^1 for young than for adult stages of growth.

Are the fluctuating characters specific or varietal?—In order to test the question whether these fluctuations in R^1 are truly varietal or may result from mixing several distinct species, the following facts have a bearing, namely:

The set of specimens selected for measurement from the Hamilton zone all belong to the one species *Rhipidomella vanuxemi* of Hall. (See Cornell University Museum Catalogue number 9139.) Twenty shells were measured for the statistics. The extremes for index R^1 for these 20 shells are 103.9 and 125.5, which shows a range of fluctuation of this index of 21.4 per cent for these 20 specimens. These 20 specimens were preserved in the same rock and bear such close resemblance to each other that I think scarcely any paleontologist would question their being one species. They are distributed in number of specimens in the following way by value of the index R^1:

2 specimens have index R^1 = 100 to 105
4 specimens have index R^1 = 105 to 110
8 specimens have index R^1 = 110 to 115
3 specimens have index R^1 = 115 to 120
2 specimens have index R^1 = 120 to 125
1 specimen has index R^1 = 125 to 130

showing emphatically that no two specimens in this small set of samples are of exactly the same shape; and, while the specimens are more numerous near the average, the difference in R^1 is such that at least 10 of them are separated by at least 1 per cent from the next specimen in the series.

This fact of positive and constant fluctuation is noticeable for all the separate lots, taken either by single faunules or by zones. It is also noticeable when the values of R^1 are tabulated for each of the Hamilton species on the basis of the type specimens as figured for each species.

Are the Hamilton "species" natural or artificial groups?—In order to test the question as to whether the described Hamilton species are natural species or only artificial groups, I determined the value of R^1 for each of the 37 specimens figured as types of the 5 species described by Hall as *O. cyclas, idoneus, penelope, leucosia,* and *vanuxemi.*

I found the range in value of this index for the whole set is 103.5 to 121 = 17.5 per cent and the average about 109.

Taking the 7 points (from 106-113), we find 23 of the 37 type specimens come within this range and at least half of the types of each species except *O. penelope* have the form expressed by this limited range in value of R^1, distributed as follows:

Two are *O. cyclas,* 2 are *O. idoneus,* 4 are *O. leucosia,* 4 are *O. penelope,* and 11 are *O. vanuxemi.*

Outside of this mean range are found 4 specimens below 106, all of which are *O. leucosia.*

Ten specimens are above 113, of which 2 are *O. cyclas*, 1 is *O. idoneus*, 5 are *O. penelope*, and 2 are *O. vanuxemi*.

It is evident from these statistics that the specimens selected as types of the 5 Hamilton species have no constancy in the value of R^1. Distribution of the type specimens in the order of value of R^1 show this character to be a constantly fluctuating character for each so-called species, and not one of the species is strictly discontinuous in respect of this character from each of the other sets of types, although selected as types of specific groups; from which the conclusion is drawn that, so far as this character is concerned, the so-called species are artificial rather than natural groups.

The mean of the fluctuations.—It is further evident from examination of the statistics that the mean of these fluctuations for the Hamilton is near 109, and the mean does not vary by 4 points either side of 109 for any of the zones in the upper Devonian.

The total range of fluctuation in a fair set of specimens from any local faunule from one end of the series to the other rarely is less than 20 points, and while on passing upward there is a clear tendency to increase of the range of this fluctuation and a drop in its mean value, the amount of this phylogenic change is but a fractional portion of the ontogenic fluctuation observed in every sample in which a couple dozen of specimens are in evidence.

Conclusions

For the present paper it is unnecessary to go into further details. The examination of the shape of the muscular scar, as expressed by the index R^3, shows the same law reported for the other indexes.

All three indexes, R^1, R^2, and R^3, point to the same conclusions, namely:

(*a*) The characters under examination are fluctuating variations in the Hamilton stage.

(*b*) Sample sets of specimens taken from the recurrent faunules of the Ithaca, Van Etten, Owego, and Swartwood zones exhibit the same characters as fluctuating variations.

(*c*) The fluctuations affect all the representatives of the genus without regard to any arrangement of the specimens into artificial specific groups and express themselves in sets of specimens derived from a single faunule or sets of faunules from a single zone.

(*d*) There is in the successive zones evidence of a tendency to move in a definite direction on passing from lower to higher geologic horizons, and this phylogenic modification is, in each case, in the same direction as the modification, expressed by individuals in their ontogenic growth.

(*e*) The expression of these characters in these Devonian samples of the race is clearly intermediate between their expression in typical samples of the race taken from the Silurian and from the Carboniferous respectively.

(*f*) It appears reasonable to generalize these facts to form the statement that phylogenic modification follows the law of ontogenic growth.

This appears to me, after making these studies, to be a more correct form of statement than to say, as we have been accustomed to do, that the ontogeny is a recapitulation of the phylogeny. From the facts it seems more probable that the direction of evolution is determined by the laws of individual growth than the converse, so far as there is any relation between the two.

(*g*) The prominent fact thus brought out, namely, the persistency of fluctuation of characters for such a long line of descent, suggests a new conception of the nature of organic variation.

The behavior of fluctuating variations indicated by this study of Rhipidomella indicates that the fluctuating is probably an effect of the fluctuating environment reacting on characters which are transmitted without fluctuation.

To use an illustration: Suppose a number of buildings were constructed according to a definite plan, in which the exact number and order of arrangement of the bricks of the walls was determined. The houses thus constructed would be alike if the bricks were of rigid material; but if the bricks were made of rubber or elastic material, the lines of the house would constantly vary with the load put on them. The conception suggested by these facts is that the plan of construction for each organism is transmitted by heredity with the same degree of definiteness for fluctuating as for unfluctuating characters, but that the reason why some characters are fluctuating is because the materials of construction are susceptible to the influence of environment during growth, and hence reflect directly the influence of the fluctuating stresses of environment.

(*h*) This elasticity of the materials of construction enables the organism to adjust itself to different environment in its growth, but the adjustment does not in any degree affect the plan of construction or whatever it may be which is concerned in the transmission of characters in heredity.

(*i*) This variability is akin to the motion of movable parts of an organism, and concerns hard parts only where they come into direct contact with environment or with active (muscularly) soft parts of the structure.

(*j*) These fluctuating characters are as important to the organic economy of the organism as are the rigid, hard parts, and are as essential in the constitution of the species; as it might be said that the joint of the elbow is as essential a part of the specific structure in making up the mechanism of a limb as are the rigid bones of the arm. The range and direction of movement provided by the flexibility of a joint is as much a specific character as is the shape of the rigid bones.

So we may generalize these facts and say that the range and direction of the fluctuating characters constitute an essential part of the specific constitution of an organism, and according to the statistics here presented appear to be transmitted with the same persistence from generation to generation as are the non-fluctuating characters which we are accustomed to regard as indicating their specific rank by ceasing to fluctuate.

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NORTH AMERICAN NATURAL BRIDGES, WITH A DISCUSSION OF THEIR ORIGIN[1]

BY HERDMAN F. CLELAND

(*Presented before the Geological Society December 29, 1909*)

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[1] Manuscript received by the Secretary of the Society February 9, 1910.

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Introduction, with Definition

There are few topographical features that excite greater interest than natural bridges. This is due, no doubt, to some extent to their rarity and to some extent to the questions which arise as to the force or forces which have been at work to produce such structures. Although rare, the total number on the North American continent is quite large. In this paper, which does not include a description of all the natural bridges of North America, thirty-eight are mentioned.

The terms "natural bridge" and "natural arch" have been so often used as synonyms, both in common parlance and in scientific literature, that it will be necessary to define the terms. In the restricted sense in which the term "natural bridge" is used in this paper, a *natural bridge is a natural stone arch that spans a valley of erosion. A natural arch* is a similar structure which, however, does not span an erosion valley. It will readily be seen from the above definitions that many of the arches which are formed by wind-blown sand, frost, solution, and wave action are not strictly natural bridges.

The classification used in this paper is one based entirely on origin, since all others that have been considered lead to more or less confusion.

A. Natural Bridges initiated by Stream Erosion

1. *By the perforation of the neck of an incised meander*

Some of the most imposing of the world's natural bridges were formed by the undercutting on the inside of the curve of an intrenched meander

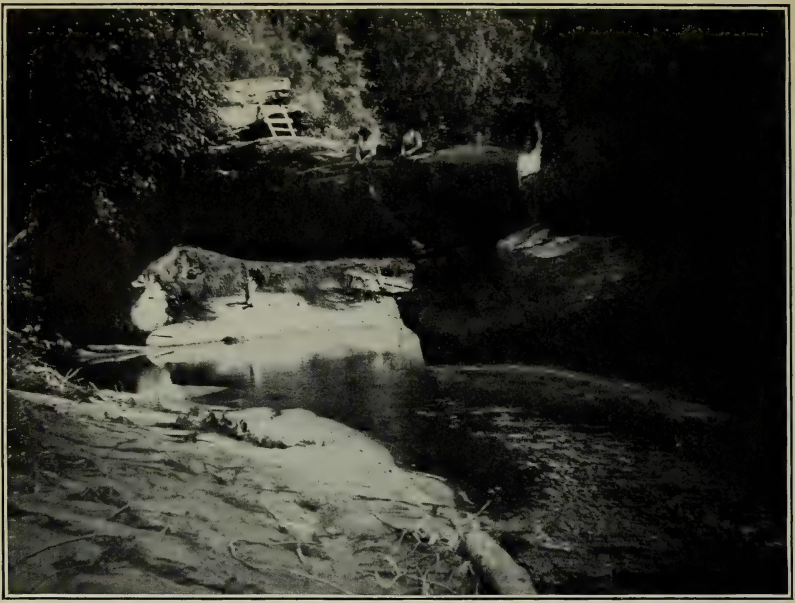

FIGURE 1.—ROCK BRIDGE ACROSS SWIFTS CAMP CREEK, NEAR CAMPTON, KENTUCKY

Formed by the perforation of an incised meander. (See text figure 1)

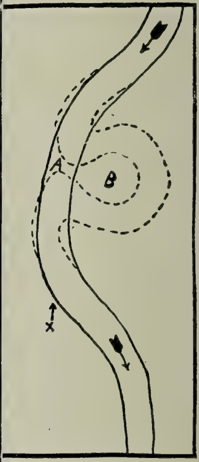

FIGURE 2.—NATURAL BRIDGE IN BAD LANDS OF SOUTH DAKOTA

This bridge, which is south of White River below the mouth of Porcupine Creek, was formed by the perforation of an incised meander. Photograph by Mr. Barnett from point "x."

ILLUSTRATIONS OF NATURAL ROCK BRIDGES

until at length an opening was made which permitted the water of the stream to cut off its meander by passing under the arch thus made.

a. Rock bridge across Swifts Camp Creek, Campton, Kentucky.—The so-called "Rock Bridge" near Campton, Kentucky (plate 18, figure 1), furnishes an excellent example of a bridge of this origin. This bridge was visited by the writer in July, 1909, and is described here for the first time. It is situated in the floor of a narrow valley from 125 to 150 feet deep, and is composed of a coarse red sandstone which is almost conglomeratic in some portions. The top of the bridge is between 15 and 20 feet above the surface of the stream; the length of the span is 50 feet and the width varies from 6 to 12 feet. The thickness of the arch is about 8 feet.

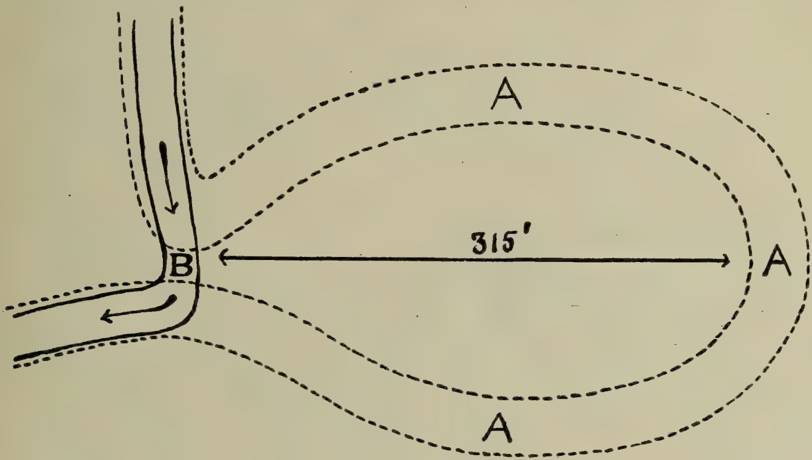

FIGURE 1.—*Diagram indicating Origin of Rock Bridge*

It will be seen from the accompanying diagram (figure 1) that the abandoned meander is long for its width, and that the sharp curve which the stream formerly made was such as to produce rapid cutting on the inside of the curve. The abandoned meander is now filled with alluvium and is cultivated. The cause of the meandering seems to have been the finding of a more resistant stratum by the stream in its downward cutting. It is possible, however, that a temporary baselevel was reached by a halt in the elevation of the region, by temporary lowering of the land, or by some temporary dam.

b. South Dakota bridge.—This bridge (plate 18, figure 2), located south of White River below the mouth of Porcupine Creek, in the Bad Lands of South Dakota, and formed of White River beds, is described by Barnett[2] as follows:

[2] Journal of Geology, vol. xvi, no. 1, January to February, 1908, pp. 93-95.

"The opening of the archway is about 12 feet high by 8 feet wide, and the thickness of the arch is something like 10 feet in a vertical direction by 7 feet in a horizontal. The gorge is about 30 feet deep, with almost vertical walls. The rock is a hard, rather blocky, light blue clay, showing typical bad-land topography."

FIGURE 2.—*Pont d'Arc* (*Ardèche*)

Scale, 1 :400,000. The origin of the bridge is evident from the map

The origin of the bridge can be readily understood by a study of the figure, which, with the illustration (plate 18, figure 2), is reproduced from the article cited.

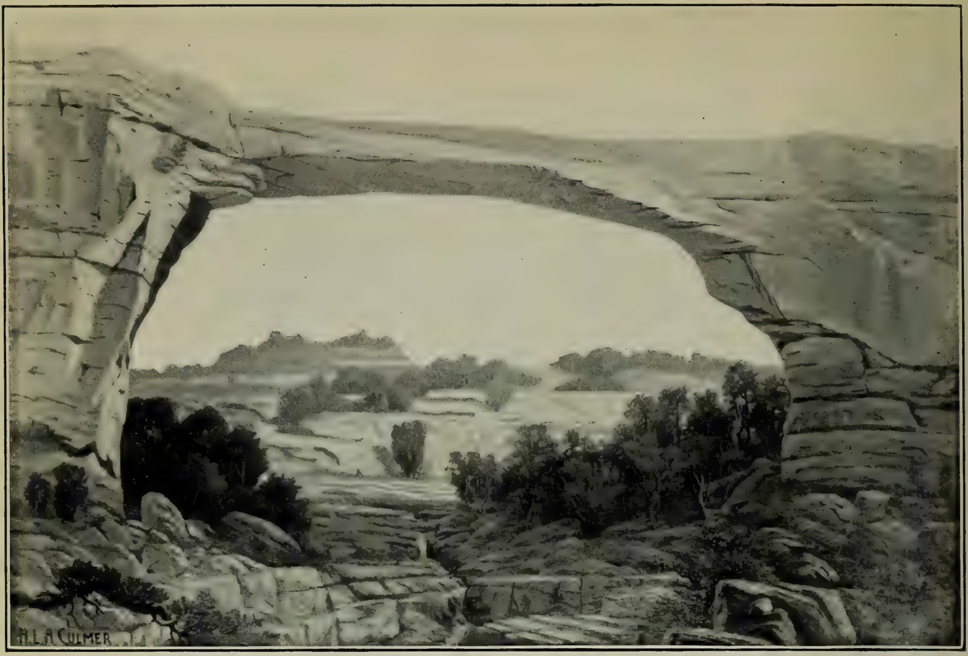

FIGURE 1.—THE EDWIN NATURAL BRIDGE, SAN JUAN COUNTY, UTAH

Photograph of a painting by H. L. A. Culmer. (See also text figure 4.) Height, 111 feet; span, 205 feet; width, 30 feet; thickness of arch, 10 feet

FIGURE 2.—THE AUGUSTA SANDSTONE NATURAL BRIDGE, SAN JUAN COUNTY, UTAH

Photograph of a painting by H. L. A. Culmer. Height, 265 feet; span, 320 feet; thickness, 83 feet; width, 35 feet

ILLUSTRATIONS OF NATURAL ROCK BRIDGES

c. Bridge at Attica, Indiana.—A natural bridge over which a roadway passes, said to be about 30 feet in height from the stream bed to the top of the bridge, spans Bear Creek near Attica, Indiana. From the very imperfect description of the bridge, which it has been possible to secure by correspondence, it appears that this bridge was formed, as in the case of the Campton bridge, by the stream tunneling through the isthmus of the incised meander.

d. Pont d'Arc, France.—A discussion of natural bridges formed by the perforation of the isthmus of incised meanders would be incomplete without a mention of the famous Pont d'Arc across the Ardêche River, in east central France.[3]

This, the most imposing natural bridge in Europe, has a height of about 60 meters and a width of 65 meters and is composed of a horizontally bedded limestone. The size of the cavity is due both to the deepening of the valley and, after the hole was made, to the crumbling of the interior surface of the arch by the agencies of the weather.

Früh includes this bridge in his division B, I, "Limited to easily soluble rocks (carbonates and sulphates)." The fact that bridges of sandstone are formed by the perforation of the neck of an incised meander, shows that mechanical erosion and not solution, as Früh supposes, is the important agent in the formation of bridges of this type. Solution is probably a negligible factor. A glance at the map (figure 2) of the region in the vicinity of Pont d'Arc shows the origin to be as described above.

e. Bridges of Southeastern Utah.—Probably the largest and most impressive natural bridges in the world are those which have been described from San Juan County, Utah. These bridges may be reached either from the north, by leaving the Rio Grande and Western Railroad at Thompson Springs, thence by stage to Moab and Bluff; or, by leaving the Denver and Rio Grande Railroad on the east, going by stage to Cortez and Bluff. The three best known bridges are about 65 miles northwest of the latter village.

The courses of the streams in this region, as described by H. L. A. Culmer (the artist who painted the pictures illustrated in this article, plate 19, figures 1 and 2), are very suggestive:

"The windings of Grand Culch [for example] are such that in one place we find ourselves separated by a wall only 60 feet in thickness from the spot we left some time before, although we have since traveled nearly a mile."

---

[3] J. Früh: Uber Naturbrücken und verwandte Formen ect. Jahrbuch der Naturwissen schaftlichen Gesellschaft (St. Gallen, 1905), p. 368.

Reclus: The earth and its inhabitants, vol. ii, Europe, pp. 96-97.

Martel: Les Cervennes, p. 291.

In the walls of these canyons, which are said to be from 400 to 1,000 feet deep, are numerous cliff dwellings, many of which are in an excellent state of preservation, together with hieroglyphics, pottery, and stone and bone implements.

The streams rarely have water in them after April, except at the time of rains and cloudbursts, at which time their erosive power must be great, since the volume of water is very large. It is reported that there is evidence that in places the water reaches a depth of 100 feet.

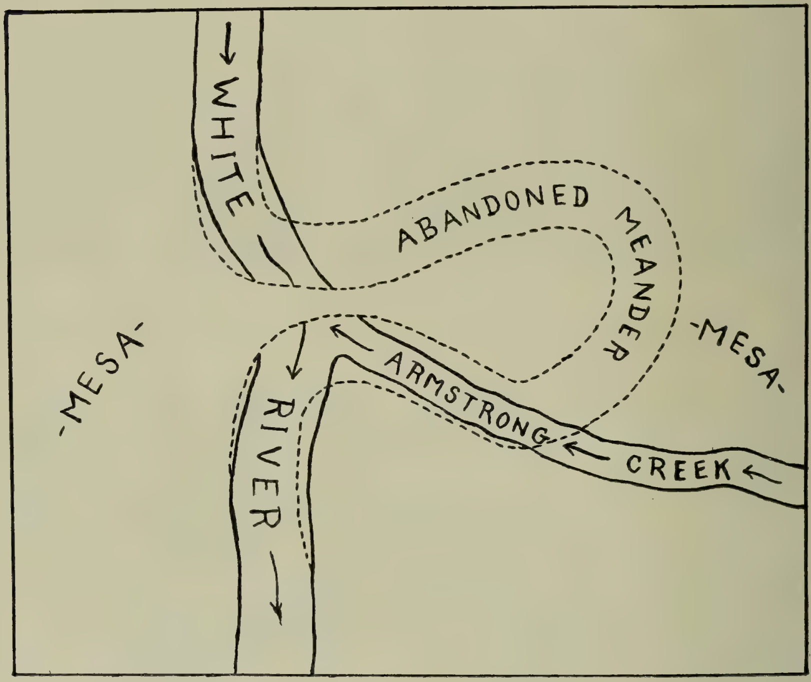

FIGURE 3.—*Diagram showing Origin of the Caroline Natural Bridge, Utah*

Modified from diagram by H. L. A. Culmer in a letter to the writer

The rock of which the bridges are composed is a buff to dull red Triassic (?) sandstone; horizontally bedded and often strongly cross-bedded. The three bridges which have been so often described, the Edwin, Caroline, and Augusta, are within three miles of each other. A fourth bridge, called Nonnezoshi, northwest of Navajo Mountain, and about 50 miles southwest of the above, discovered by Utah Archæological Expedition last summer (1909), has a length of 273 feet and a height of 308 feet, making it, as far as known, the largest natural bridge in the world.

Since the writer has not visited this region, and consequently has not made a study of the bridges on the ground, his conclusions are necessarily based on the observations of others. In the case of the Caroline bridge, the mode of formation seems to be the same as that of the foregoing bridges, judging from the rough sketches of the region submitted to the writer, one of which is produced here (figure 3). It is possible that in this case the perforation of the neck of the meander was hastened by the work of Armstrong Creek.

The Edwin bridge (plate 19, figure 1) offers a variation from the type already discussed, as will be seen by the accompanying diagram (figure 4).[4] The neck of land perforated was not a meander, but a narrow strip of land at the juncture of two streams. It appears from the evidence

FIGURE 4.—*Diagram showing Origin of the Edwin Bridge, Utah*
Modified from diagram by H. L. A. Culmer in a letter to the author

that the perforation was made by the lateral cutting of the former Edwin Creek by Armstrong Creek or by a combined action of the two.

The information concerning the Augusta (plate 19, figure 2) and Nonnezoshi bridges is very incomplete, but from what could be gathered from those who had visited them, and also from the fact that the bridges are composed of the same material as the Edwin and Caroline bridges, and are situated in a region of incised meanders, it seems probable that they were formed in the same manner as the Edwin and Caroline bridges.

[4] These diagrams are from rough sketches made by Culmer to show in general the courses of the present and former streams, and are not drawn to scale.
W. W. Dyar: Century Magazine, vol. 68, August, 1904.
H. L. A. Culmer: Technical World, September, 1908, pp. 49-55.
Letters to the writer from Mr. H. L. A. Culmer, 1907.
Other descriptions have appeared in the Sunday supplements of several daily papers, the National Geographic Magazine, Scientific American, Collier's.

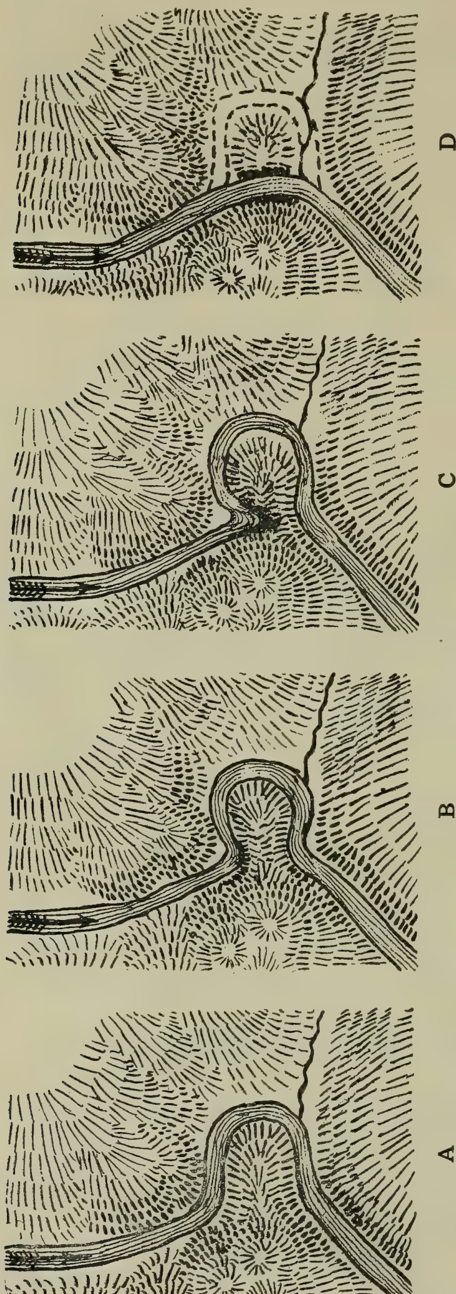

FIGURE 5.—*Maps showing Location of present and former Channel of the Washita River, Oklahoma, after Gould*

Prof. C. N. Gould, in a letter to the writer, states that a natural bridge which probably spanned the river when the rock of the meander was first cut through has disappeared.

f. Bridges of Le Perle Creek, Wyoming, and Buffalo Gap, South Dakota.—The information concerning these two bridges is so meager that nothing can be said of their origin except that they should possibly be included in this group. The Le Perle Creek bridge is composed of "Tensleep sandstone, a white massive formation, moderately hard and presumably with siliceous cement; the span is about 35 feet, the greatest height 10 feet, and the width about 25 feet."[5]

The Buffalo Gap bridge is composed of "Unkpapa sandstone, fine grained, massive, pinkish in color, and with supposed siliceous cement. The span is about 8 feet and the width 6 feet."[5]

g. Discussion of a former natural bridge of this type in Oklahoma.—Through the courtesy of Prof. C. N. Gould,[6] I am able to use the following series of maps (figure 5) showing the location of the courses of the present and former channels of the Washita River

[5] N. H. Darton in a letter to the writer, February 17, 1907.
[6] A letter from C. N. Gould, January, 1910.

where it crosses the Arbuckle Mountains 8 miles south of Davis, Oklahoma.

"The cliffs on the east side of the stream are from 150 to 300 feet high and are composed of solid limestone. At some point between 'C' and 'D,' as indicated in this map, the stream evidently found a course along a folding plane or joint along the narrowest part of the interposed wall. This condition continued until all of the stream ran through this channel and the old channel was abandoned. Later the bridge which evidently spanned the stream fell in."

2. *BY POT-HOLE ACTION*

Theoretically bridges of small size should result by the enlargement of the diameter of pot-holes near their bottoms until the walls of two or more such holes are worn through, thus permitting the water of the stream to pass under an arch. At Shelburne Falls, Massachusetts, and in many other stream beds, partial bridges of this origin occur, but complete bridges of this type are rare.

a. Bridge spanning Kicking Horse River, British Columbia.—The rock of which this bridge, near Field (plate 20, figure 1), is composed is an impure limestone in which a strong vertical cleavage has been produced, the cleavage being so strong that the synclinal structure of the rock of the ledge is often rendered indistinct.

Formerly a ledge of rock produced a fall or rapid in the river at this place. In the course of time two series of pot-holes were developed (as is shown in the diagram, figure 6), which gradually enlarged, especially near their bottoms, until they finally opened into one another. The openings were small at first and only a small quantity of water poured through, but when the wall was broken through they rapidly enlarged, until now the entire volume of the stream flows under the ledge. The height and width of the bridge (figure 6) are difficult to estimate, because of its irregularity and also because of the great volume of water which pours through and fills the opening. The average width of the arch is about 10 feet and the length between 5 and 8 feet. The height of the top of the bridge above the stream is in places not more than 3 feet and the thickness of the arch is probably between 6 and 8 feet.

b. Lamoille River Bridge, Vermont. — A bridge which spans the Lamoille River at low water (shown in the accompanying illustration, plate 20, figure 2) appears to have been formed by pot-hole action, judging from the information furnished by Mr. M. A. Gibson.[7] The width of the ledge through which the opening has been made varies from 6 to 10 feet. The mica schist of the stream bed is full of pot-holes, both

[7] M. A. Gibson in a letter to the writer, 1906.

above and below the bridge, some of which are very deep. The water flows under the ledge (plate 20, figure 2) between "1" and "2." At "3" (upstream) the stream flows over a fall into a basin called the "death pot," and reappears at "4."

3. *EROSION ASSISTED BY FROST ACTION*

a. Yellowstone Natural Bridge.—The origin of the natural bridge across Bridge Creek, Yellowstone National Park, is probably unique, since it is unlikely that the conditions that made it possible have occurred elsewhere.

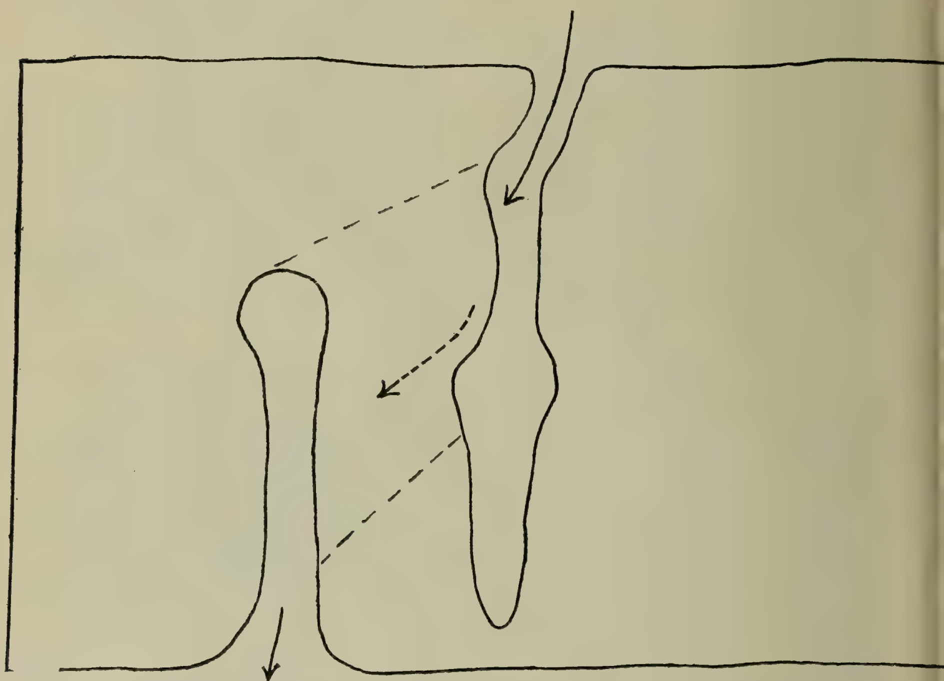

FIGURE 6.—*Diagram of the natural Bridge across Kicking Horse River*

Indicates that the bridge was formed by pot-hole action

The bridge (plate 21, figure 1), which consists of two vertical layers of lithoidal rhyolite, stands 40 feet above the stream bed and has a length of span of about 30 feet. The layers of which the bridge is composed are slightly curved and are separated by open crevices with roughened scoriaceous walls (plate 21, figure 2). Of the two slabs forming the bridge the eastern is 2 feet thick at its ends and thinner in the middle; this is separated from the western slab, which is 4 feet in thickness by a space of about 2 feet.

FIGURE 1.—THE NATURAL BRIDGE ACROSS THE KICKING HORSE RIVER, NEAR FIELD, BRITISH COLUMBIA, SEEN FROM BELOW

(See text figure 6)

FIGURE 2.—THE NATURAL BRIDGE WHICH SPANS THE LAMOILLE RIVER, VERMONT, AT LOW WATER

The water flows under the ledge between 1 and 2. At 3 the stream flows over a fall into a basin (called the death pot) and reappears at 4

FIGURE 1.—BRIDGE OF LITHOIDAL RHYOLITE, BRIDGE CREEK, YELLOWSTONE PARK
Photograph by Walcott, U. S. Geological Survey

FIGURE 2.—VERTICAL, PLATY STRUCTURE OF THE RHYOLITE
This structure made it possible for the stream, with the assistance of frost, to make the Yellowstone National Park bridge. Photograph by Iddings, U. S. Geological Survey.

ILLUSTRATIONS OF NATURAL ROCK BRIDGES

"The explanation of the formation of the bridge is as follows: The stream which flows underneath the bridge has been able to excavate, owing to a former waterfall and the peculiar platy structure of the rhyolite, in which curved layers of extremely different physical texture and friability offered a favorable site for attack by frost and water."[8]

The excavation was accomplished by the water which flowed over the fall (now the top of the bridge) excavating with its sediment the rock at its base, assisted by the separation of the thin plates of lava by the expansion of the water on freezing. This excavating continued until a layer of more porous lava (represented by the space between the slabs composing the bridge) was found, which permitted the water to flow downward into the cave. This process was repeated, thus producing a bridge made of two vertical layers.

b. Remnants of lava stream roofs not included.—The remnants of lava stream roofs are not included as natural bridges, since they are to be classed as arches. It should be stated, however, that arches of this sort perform the functions of bridges, since they permit men and animals to pass over a cavity which otherwise it would be necessary to bridge.

4. *TRAVERTINE-CEMENTED STREAM DEPOSITS UNDERCUT BY STREAM EROSION*

The writer has neither seen nor been able to learn of any bridges of this origin in North America. Professor Früh cites several examples from Europe and South America which should be mentioned here, in order that our classification may be as complete as possible.

a. Bridges in Arcadia and Messina, Greece.—In northern Arcadia, in Greece, a brook disappears under a tunnel 100 meters long whose roof consists of earth and debris cemented by travertine. It supports fields, a few trees, and a roadway.[9]

Another in northern Messina, in Greece, is described as being a tunnel of mountain debris cemented by travertine.

b. Puenta del Incas, South America.—Another cited by the same writer,[10] from Güssfeldt, is near the Bañas del Inca. It is 40 meters long and 40 meters broad and consists of valley debris cemented by travertine over which a compact layer of travertine has been formed.

5. *BY THE UNDERCUTTING OF A PETRIFIED LOG*

An unusual natural bridge (plate 23, figure 1) formed by stream erosion is that in the petrified forest of Adamana, Arizona, where a petrified

[8] H. F. Cleland: American Journal of Science, vol. 20, August, 1905, p. 123.
[9] Früh: Naturbrücken, ibid., p. 363.
[10] Ibid., p. 363.

log of agatized wood has been undermined by stream erosion until it now spans a true valley of erosion. The canyon or gulch has a north direction and is very precipitous, beginning only 200 yards above the bridge and rapidly broadening in its descent. At the point where the bridge crosses the canyon it is about 30 feet wide, but the trunk lies diagonally across and measures 44 feet between the points at which it rests on the sides of the canyon. The canyon is here about 20 feet deep. The total length exposed is 111 feet, so that more than 60 feet of the upper part of the tree lie out on the left bank of the canyon. At about the middle of the canyon the tree measures 10 feet in circumference, which implies a diameter of over 3 feet. The rock in which the log was imbedded is very soft and easily eroded. The Santa Fe Railroad Company has placed two piers (shown in the illustration) under the bridge to support it. These supports are, however, of little use and are very unsightly.[11]

6. *BY THE HEADWARD CUTTING OF TWO STREAMS*

Certain natural bridges near the station Natural Bridge, in Powell County, Kentucky, near the middle fork of Red River, should be discussed here because of their peculiar erosional origin. The country in which they occur is a high plateau region, in a mature stage of development (plate 22, figure 2), composed of heavy bedded strata of carboniferous sandstones and limestones, which have been deeply dissected by stream erosion, forming deep valleys with divides, which in many places are only a few feet wide. The bridge from which the station Natural Bridge received its name (plate 22, figure 2) is one of these and is perhaps the most imposing of them, the arch itself being 32 feet high and the width of the cavity at the bottom being about 66 feet. The width of the span is 20 feet and its thickness is about 12 feet. This arch and two others in this region were formed by the headward cutting of two streams the headwaters of which have almost met (see map, figure 7), leaving a divide which, in the case cited, is but 20 feet in width. The cavity now spanned by the bridge was produced by the combined action on the divide of water, wind and frost. Two other "bridges" occur near the above.

These arches were first described by A. M. Miller,[11a] who gave the correct explanation of their origin.

7. *BY REMOVAL OF UNCONSOLIDATED MATERIAL UNDERLYING A RESISTANT STRATUM*

a. Switzerland. — Unconsolidated material underlying a resistant stratum may be carried away in suspension by water which first seeped

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[11] For a discussion of the petrified forest, see "The petrified forests of Arizona." L. F. Ward, Smithsonian Report, 1899, pp. 289-307.

[11a] A. M. Miller: Natural arches of Kentucky, Science, vol. 7, June 24, 1898, p. 845.

Figure 1.—The Bridge at Natural Bridge Station, Powell County, Kentucky

Formed by the headward cutting of two streams. Photograph used by courtesy of the Lexington and Eastern Railroad

Figure 2.—Configuration of the Country near the Station Natural Bridge, Powell County, Kentucky

Showing the conditions favorable to the formation of bridges by the headward cutting of streams. (See text figures 6 and 7)

ILLUSTRATIONS OF NATURAL ROCK BRIDGES

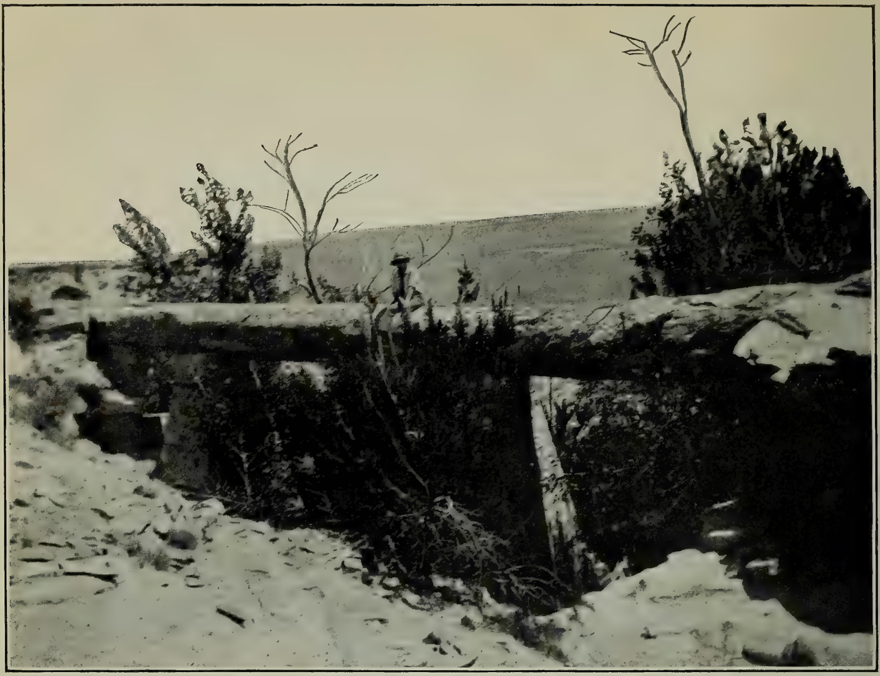

FIGURE 1.—A PETRIFIED LOG FORMING A BRIDGE ACROSS A RAVINE IN THE PETRIFIED FOREST OF ARIZONA NEAR ADAMANA

FIGURE 2.—NATURAL BRIDGE, BIG BAD LANDS, SOUTH DAKOTA
Photograph by Darton, U. S. Geological Survey

ILLUSTRATICNS OF NATURAL ROCK BRIDGES

through a joint or other crack in the harder overlying rock, thus forming a natural bridge. What may be considered a type of this mode of formation is a bridge over the Thur (described by Früh[12]) near Krummenau, in Switzerland. In this region the underlying rock consists of a series of alternating beds of southerly dipping marls, sandstones and

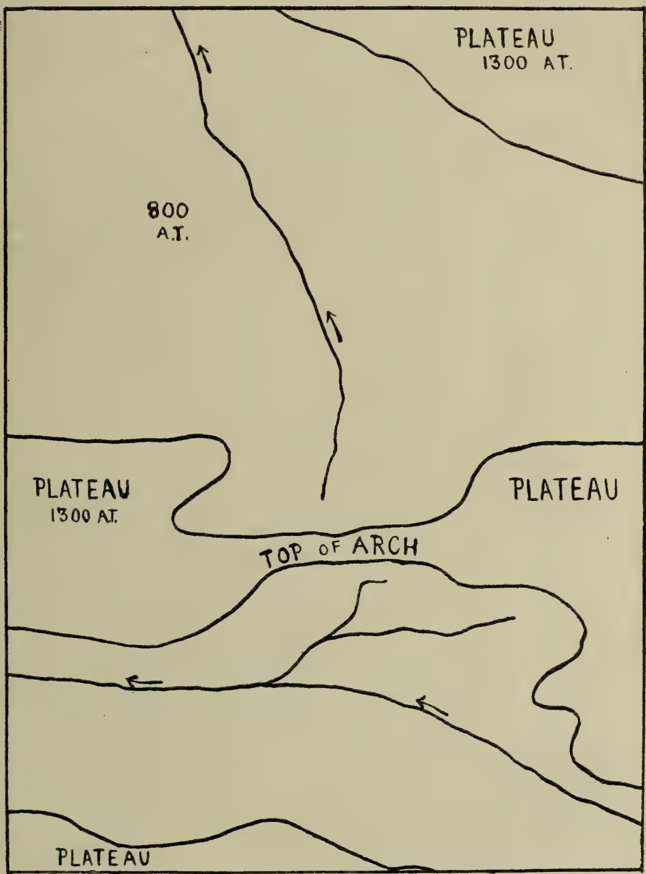

FIGURE 7.—*Map indicating Formation of Natural Bridge in Powell County, Kentucky, by the headward Cutting of two Streams in a Plateau Region*

resistant, fissured conglomerates several meters thick. Keeping these conditions in mind, the formation of the bridge is clear. The river loses itself here and there through fissures in the conglomerate to a layer of marl. Instead of working chemically, the water carries the marl away in suspension, thus leaving a natural bridge or tunnel. Since the stream in

[12] J. Früh: "Naturbrücken," etc., p. 369.

this place has cut through several layers of conglomerates and marls before reaching its present position, it is probable that this process has been repeated several times, perhaps with the formation at different levels of several natural bridges that have since disappeared.

b. Big Bad Lands of South Dakota.—This bridge (plate 23, figure 2) spans the valley of a temporary stream and was evidently formed as described above. It can not, however, be considered a typical example. "The rock consists of a coarse sandstone, rather soft, and apparently with siliceous cement."[13]

c. Earth bridges.—To the above should be added small earth bridges. Such earth bridges occur where a muddy or alluvial valley bottom covered with turf is in process of trenching by head erosion. The low water drainage becomes subterranean, following cracks or joints, along which it develops channels. Such bridges are necessarily very temporary and the streams very small.

B. Bridges initiated by Wave Action

One could cite scores of examples of arches which have been produced by wave action, but few of these should strictly be considered as natural bridges. The natural bridge at Santa Cruz, California (plate 24, figure 1), however, should be so considered, since it does span a valley of erosion. This bridge was described by Shaler[14] as the portion of an arch that has fallen in, the space being widened by the waves which roll beneath the bridge. He states further that the horizontal strata are of limestone and are thus easily soluble by the waves. This latter statement is an error, since the upper part of the bridge consists of Pleistocene deposits a few feet thick resting on horizontal diatomaceous shales of Miocene age. The cavity was excavated by the mechanical action of the waves and not by solution. "This bridge occurs on the edge of a marine terrace and was formed by the waves eating in under the nearly horizontal shale beds forming a cave, the roof of which dropped in behind the bridge, leaving the arch across the entrance."[15] Several of these bridges have been formed at different times along this terrace, but they usually last but a short time. Photographs of two or three are still preserved.[16]

It will be seen that such a structure could be termed either a natural arch or a bridge without going far astray. It has, however, been in-

[13] N. H. Darton in a letter to the writer, February, 1909.
[14] Shaler: Sea and Land, p. 18.
[15] Letter from Prof. J. C. Branner.
[16] Letter from Dr. Ralph Arnold.

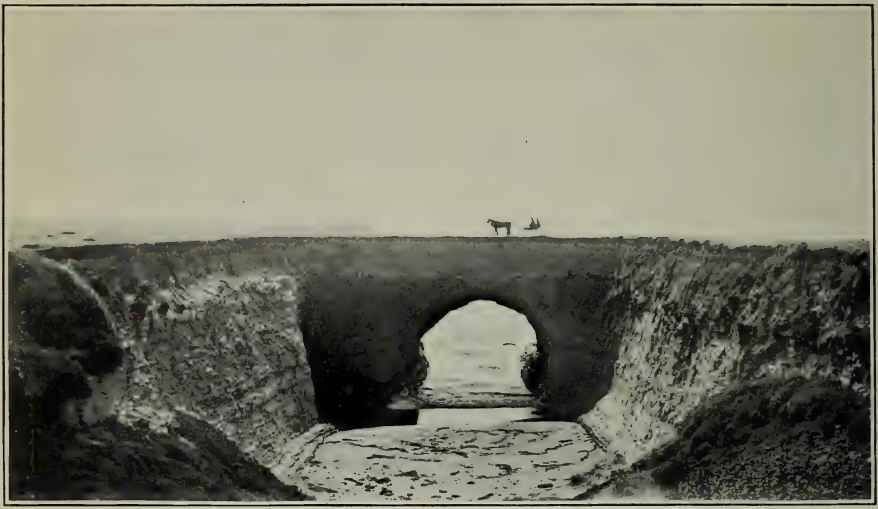

FIGURE 1.—A NATURAL BRIDGE IN MIOCENE SHALES, SANTA CRUZ COUNTY, CALIFORNIA

Formed by wave erosion. Photograph by Arnold, U. S. Geological Survey

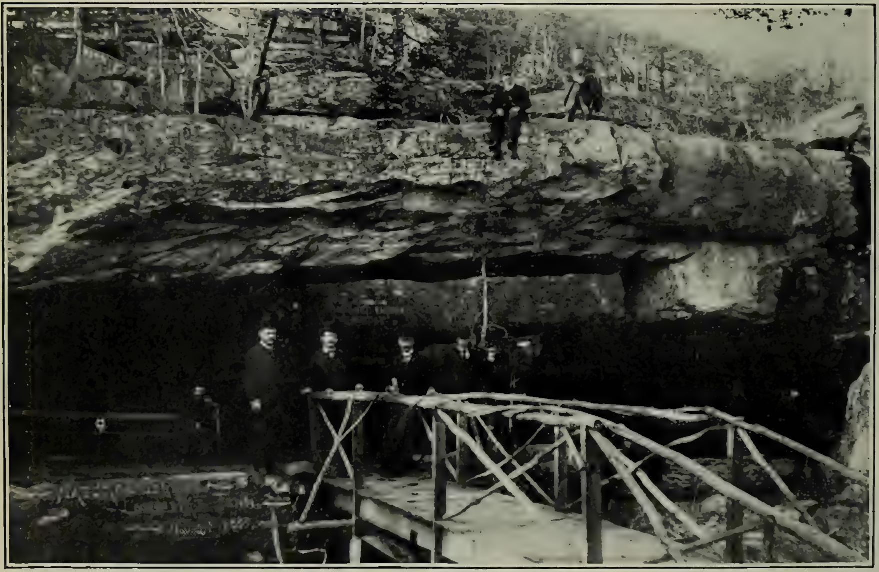

FIGURE 2.—A NATURAL BRIDGE OF YELLOW SANDSTONE SPANNING A SMALL BROOK ON LOOKOUT MOUNTAIN, TENNESSEE

Formed by the widening of a joint

ILLUSTRATIONS OF NATURAL ROCK BRIDGES

cluded among natural bridges because the valley which it spans for a portion of the year, at least, probably contains a small stream. The valley can not, however, be said to be formed by stream erosion.

C. Bridges initiated by Solution

In regions in which the surface rock is thick and fairly soluble tunnels as well as natural bridges may be formed, the only difference between a tunnel and a bridge being the greater length of one than the other. Probably the greater number of the natural bridges of the world—though certainly *not the most imposing*—are to be included in this division.

1. *BY SEEPAGE*

Natural bridges may be formed by seepage through a joint or other crack in the bed of a stream, usually approximately at right angles to the course of the stream, thence along a bedding or other plane and discharging under a fall or rapid.

a. The Virginia Natural Bridge.—This remarkable natural bridge may be considered a type of bridges formed by seepage. In bridges of this character the cavity which later produced the bridge was formed by water percolating through a joint or fissure athwart the stream, thence along a bedding plane and emptying under a fall or rapid of the stream. The channel thus formed was gradually enlarged until all the water of the stream was diverted from the stream bed below the point of ingress, leaving a bridge. The height of the arch of the natural bridge above the stream will naturally depend upon the amount of cutting subsequent to the formation of the bridge, and to the weathering of the under side of the arch. Bridges formed in this way can readily be distinguished from those formed by the caving in of all but a small portion of the roof of a cavern by the fact that the top of bridge of the former was plainly at one time the bottom of the valley.

"On the north side[17] the summit of the bridge is 236 feet above the water, and this part of the arch has a thickness of 44 feet and a span of from 45 to 60 feet. The western edge is about 10 feet higher and the eastern edge about 10 feet lower than the central point."

b. The Oklahoma Natural Bridge.—A natural bridge of unusual origin occurs 15 miles southeast of McAlester, Oklahoma.[18] The limestone, which is almost vertical in this place, permitted the water of the

[17] C. D. Walcott: National Geographic Magazine, vol. 5, 1893, pp. 60, 61.
[18] The information concerning this bridge was obtained from Prof. C. N. Gould in a letter, January, 1910.

stream to flow down along a bedding plane, thence through a crack or joint from which it issued beneath a fall which existed at the contact of the limestone and a shale. The arch is said to be about 10 feet high above the stream level and probably 25 feet across.

c. The Massachusetts Natural Bridge.—The marble natural bridge at North Adams, Massachusetts, furnishes another illustration. With the possible exception of the Virginia Natural Bridge, that in North Adams (plate 25) is one of the most interesting and unique in the eastern half of the continent. Hawthorne in his *American Note Book* speaks of its beauty and of the pleasure he often took in visiting it. It spans Hudson Brook, a small stream emptying into Beaver Creek, a tributary of the Hoosac River.

A short distance above and below the bridge the brook flows through a gorge of white marble 30 to 60 feet deep and from 5 to 40 feet wide, the average width above the bridge being from 5 to 10 feet and below from 10 to 30 feet. The gorge is cut in a coarsely crystalline marble of Cambro-Ordovician age which belongs to the Stockbridge formation.

The top of the bridge is 44 feet above the water of the stream, the arch itself being about 8 feet thick in the middle. The span of the bridge is less than 10 feet long and the width, at present, is 25 feet. Hitchcock[19] states that when he studied the region (before 1839) there were two natural bridges, "though the upper [?] one is much broken." Only one bridge is in existence at present, but the second one, described by Hitchcock, appears to have been below, not above, the present one.

"On examining the course of the stream and the rock in the vicinity of the North Adams Natural Bridge, one is struck with the width of the joints and the fact that the stream has for a portion of its course followed the joint planes."[20]

The bridge was formed as follows: When the stream flowed into the gorge through the ancient channel, it plunged over a fall into a preglacial valley. Some of the water in the joint plane nearest the present bridge seeped through an approximately horizontal crack a short distance under the present arch of the bridge. The solvent power of the water containing carbon dioxide (CO_2) gradually increased the size of the crack until it was still further enlarged by the erosion of the stream. The stream was finally entirely diverted from its former channel to its

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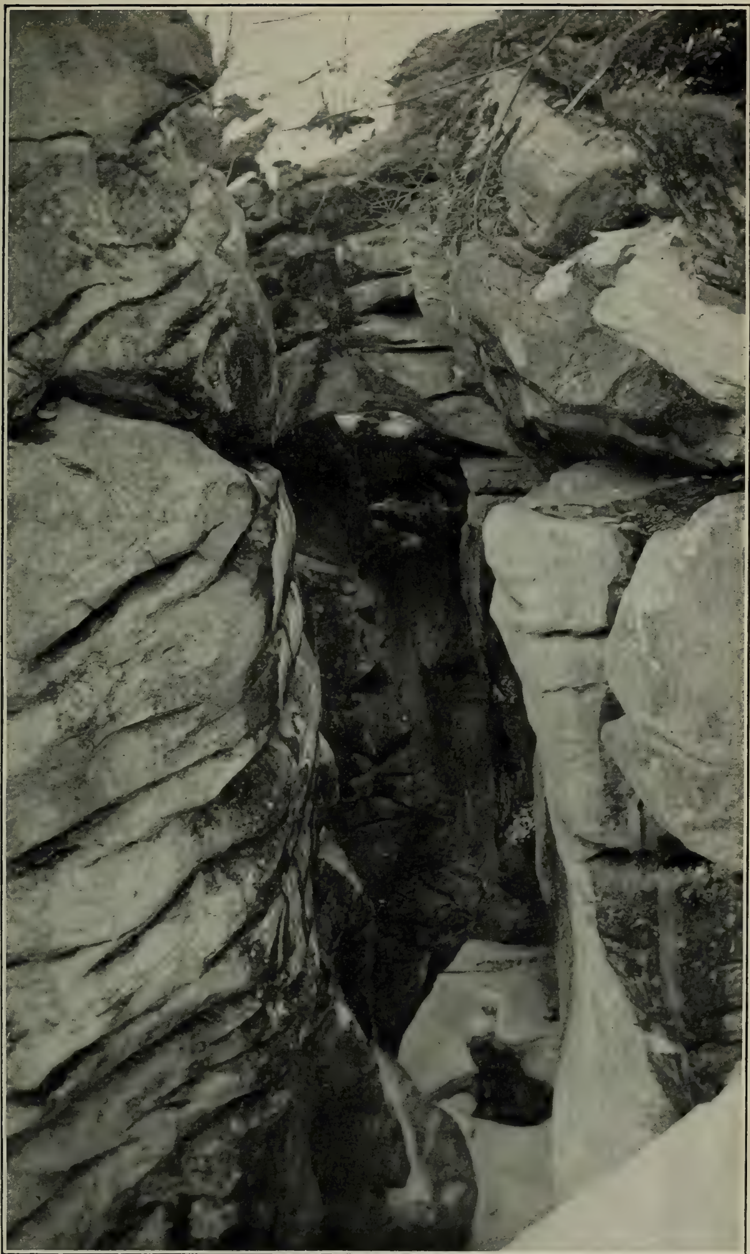
[19] Edward Hitchcock: Geology of Massachusetts, vol. 1, 1841, pp. 287-288.

[20] H. F. Cleland: Formation of natural bridges, American Journal of Science, vol. xx, August, 1905, pp. 120, 121.

E. O. Hovey: Celebrated American caverns, pp. 14 and 206.



MARBLE NATURAL BRIDGE IN NORTH ADAMS, MASSACHUSETTS

present course. The gorge from the dam to the preglacial valley is a succession of broken pot-holes varying in size up to 6 or 8 feet in diameter, showing that after the tunnel was made the gorge was largely excavated in this way. The preglacial valley in which the Hudson Brook flows below the gorge is broad, but to some extent choked with glacial drift.

d. Illustrations of bridges formed by the widening of a joint.—By the widening of a joint near the source of a spring a portion of the country rock may be separated from the parent ledge so as to form a bridge. A good example of a bridge of this origin is the Natural Bridge at Chattanooga, Tennessee. The bridge (plate 24, figure 2) is a small one, being 8 or 10 feet in height, and spans a stream which has its source in a spring a few yards away. It is clearly formed by the widening of a joint, which thus separated the rock of which it is composed from the parent ledge. The bridge is used to some extent by foot passengers.

From Shepherd's[21] descriptions of two bridges in Green County, Missouri, it seems probable that they also are of this type, being formed by the widening of a joint or fissure near the mouth of a cavern.

One of these bridges is described as follows: This beautiful bridge (township 28 north, range 21 west, section 3, northeast ¼ of northeast ¼) abruptly heads a narrow gorge about 100 feet wide, which extends up from the bottom lands of the James River. The country road formerly passed over it. This bridge is 50 feet long, 15 feet wide, and 12 feet high.

Another bridge described is situated 4 miles east of Springfield, Missouri.

2. *BY THE COMBINED ACTION OF SUBAERIAL AND SUBTERRANEAN EROSION*

The following statement is one which, with a slightly modified phrasing, has done service in the geologies and geographies for a generation or two as an explanation of the origin of natural bridges:

> "As a cavern enlarges and the surface of the land above it is lowered by weathering, the roof at last breaks down and the cave becomes an open ravine. A portion of the roof may remain, forming a 'natural bridge.' "[22]

The accompanying familiar diagram (figure 8) illustrates the theory.

Theoretically one would expect to find a large number of bridges of this origin, but investigation has failed to bring to light any well-defined examples.

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[21] E. M. Shepherd: Geology of Green County, Missouri, vol. xii, 1898, pp. 117-118.
[22] Norton: The elements of geology, 1905, p. 46.

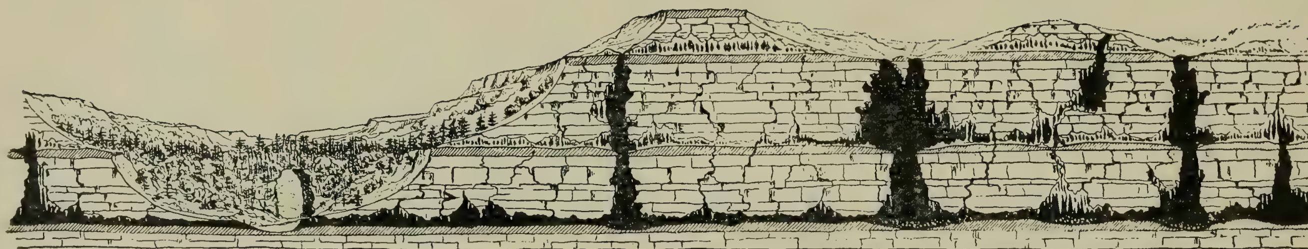

FIGURE 8.—*Diagram indicating Formation of Bridges from the "Remains of a great Cavern."*

Until recently no other explanation was considered in the geologies and geographies of North America. The diagram is reproduced from Shaler's "Aspects of the Earth"

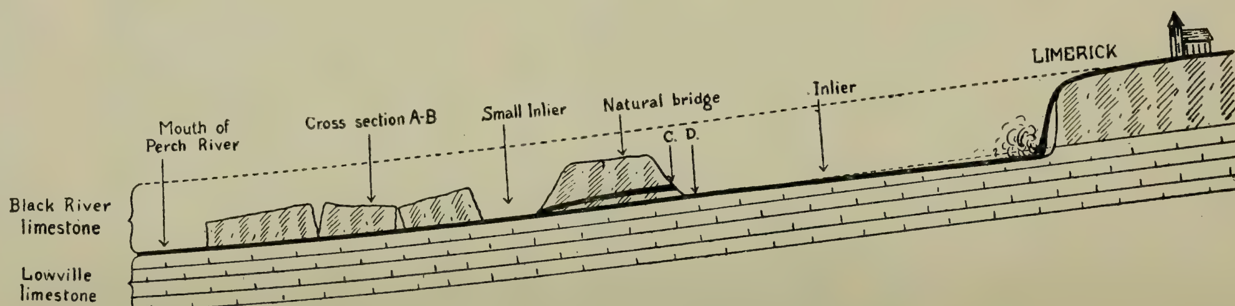

FIGURE 9.—*Section of Perch River Natural Bridge*

C, high-water subterranean course through the joints and cracks of the rocks; normal subterranean course on the surface of the Lowville limestone (after Ruedemann)

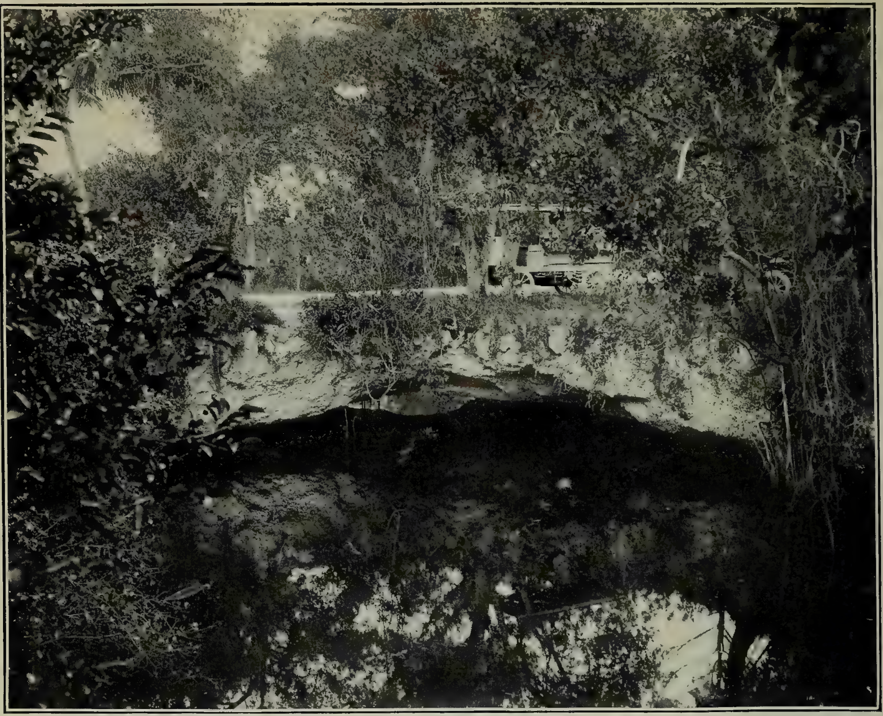

FIGURE 1.—NATURAL BRIDGE ACROSS ARCH CREEK, NEAR MIAMI, FLORIDA
Composed of oölitic limestone

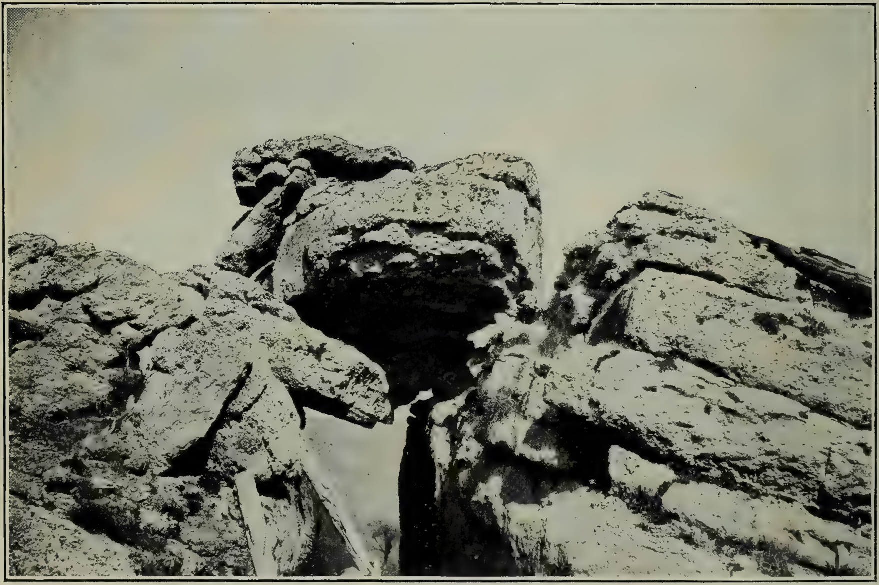

FIGURE 2.—NATURAL BRIDGE FORMED BY GRAVITY, BIG HORN MOUNTAINS, WYOMING
Photograph by Walcott, U. S. Geological Survey

ILLUSTRATIONS OF NATURAL ROCK BRIDGES

In a region of thick limestone, such as Edmonson County, Kentucky, where it is said there are 100,000 miles of underground caverns, one would expect natural bridges to be found in a later stage of physiographic development; for, as the surface of the land is lowered by subaerial erosion and the caverns are enlarged by subterranean erosion and solution, a time must, theoretically, come when all but small portions of the cave roofs will disappear, thus forming natural bridges. Caves formed in this way will differ in several particulars from those described under C 1. For example, as the land is lowered and the sink-holes are enlarged, the portion of the cavern roof left standing to form the bridge will be between wide basins which were originally sinks and which will clearly show their origin, since the valley will widen rapidly on either side of the bridge, thus showing their sink-hole origin. This consideration is well shown from a study of the topographic and geologic maps of limestone regions, particularly those of the Kingston, Tennessee, and Bristol, Virginia, folios of the U. S. Geological Survey.

3. *BY THE PARTIAL CAVING IN OF SUPERFICIAL TUNNELS*

Many bridges, initiated by solution, are formed by the partial caving in of the roof of a superficial tunnel, the tunnel being formed either (1) by the water of a stream which disappears in the joints of a limestone stratum and appears further down stream; or (2) by an underground stream emerging as a spring (the underground stream may have a single channel for but a short distance), the major portion of the roof of the tunnel collapsing and leaving one or more natural bridges.

a. Florida bridges.—There are a number of bridges of this origin in Florida. Large bridges occur on the Chipola River above Marianna; on the Saint Marks River south of Tallahassee, and on the Santa Fe River northeast of High Springs, the distance between the rise and sink of the latter stream being two or three miles. The natural bridge on the Chipola River, one-quarter to one-half mile wide, is submerged during high water, and a broad surface channel which crosses the one near High Springs is said to carry a portion of the flood water of the Santa Fe. The breadth of the surface channel near High Springs suggests that the natural bridge of the Santa Fe River may have been formed by the first method outlined in this paragraph. The bridge across the Chipola appears from the accounts to have a similar origin to the last.

A natural bridge across Arch Creek near Miami, composed of oolitic limestone (Pleistocene), more nearly satisfies our conception of a natural bridge than any other in Florida. In this case the arch (plate 26, figure 1) stands some 12 to 15 feet above the normal surface of the stream.

A small bridge of light gray marl is reported near Homosassa, Walton County, Florida, the width of the stream being about 20 feet and the width of the bridge, from the "sink" to the "rise" of the stream, being about one-third or one-fifth of a mile.[23]

b. New York bridges.—The New York natural bridges in Jefferson County are formed by the first method. The largest of these is one across Perch Creek (figure 9), but even this one does not fulfill the usual conception of a natural bridge, since the arch does not stand much above the surface of the stream at low water and is submerged at high water.

"The water flows underground in the Black River limestone, which is full of enlarged joints, and runs underground on the summit of the Lowville, which is less soluble. It eats out a channel in the basal portion of the Black River, and as this has no great thickness, it is not self-supporting over the arches, and much of the roof slowly slumps as the process goes on. It is here entirely a process of limestone solution and of slow slumping of the roofs due to non-support. The water goes down a widened joint athwart the stream course, and follows joint planes more or less parallel with the course, eating them away until they hold a larger and larger portion of the stream's capacity. There are several instances in the district where the entire flow is usually underground, but where the bare limestone surface of the channel shows clearly that the underground channel can not care for the entire volume during floods. Slight falling of the rocks is often influential in putting the streams back to the surface again."[24]

In one place the stream is brought to the surface, where it cuts across a preglacial channel at about right angles, emerging from under one wall of limestone and disappearing under the opposite wall.

c. Iowa bridges.—In the report on Jackson County, Iowa, Savage[25] describes a "series of natural bridges that have been developed by the waters of a small creek eroding a subterranean passage." "The upper or most northerly bridge has a length of 150 feet across the gorge and a width of about 60 feet." "[The stream] has carved a passage 50 feet in height beneath the span of the bridge." "About 8 rods farther down the stream a second arch crosses the ravine." The bridges are stated as being the result of the partial caving in of a cave roof.

d. Missouri Natural Bridge.—A natural bridge in Miller County, Missouri, differs from the other bridges which have been included in this

[23] Modified from descriptions given by Dr. E. H. Sellards in a letter to the writer and from the Second Annual Report of the Florida Geological Survey, 1909, pp. 36-37.

[24] H. P. Cushing in a letter to the writer, June 8, 1909. See also R. Ruedemann, "Types of inliers observed in New York." New York State Museum Bulletin no. 133, 1909, p. 175.

[25] T. E. Savage: Geology of Jackson County, Iowa, Geological Survey, vol. xvi, Annual Report, 1905, pp. 571-573.

division in that "a crevice or open joint penetrating the entire thickness of the roof has undoubtedly been one of the chief factors determining the tunnel." "Large slabs of rock have fallen from the under side of the bridge along the crevice." "The opening underneath the bridge is 200 feet long, 20 feet high, and 50 feet wide."[26]. It appears from the above that the bridge owes its origin to a longitudinal crack through which the water seeped, enlarging a tunnel beneath the surface.

e. Bridges in western Oklahoma.—Certain bridges in the Gypsum Hills of western Oklahoma may belong to this division. It is possible, however, that they should be included under C, 2. No descriptions of these bridges are available.

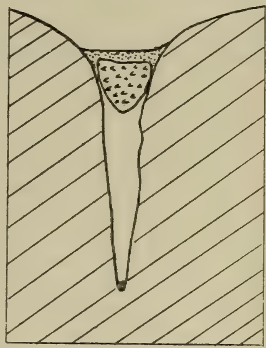

FIGURE 10.—*Diagram to show how a natural Bridge may be formed by Gravity*

A boulder fallen from the mountain side has lodged in a narrow ravine

SUMMARY OF DIVISION C

It will be seen from the above that bridges initiated by solution are of three or four types: (1) Those formed by seepage along joints and bedding planes, thence emptying under a fall or rapid; (2) those formed in a region of thick limestone or gypsum by subaërial erosion, with the accompanying enlargement of the caverns and the sinks, and (3) by the local remains of comparatively superficial tunnels.

D. Bridges formed by Gravity

1. *BY A STONE WEDGED IN A NARROW CHASM*

In mountainous regions, where erosion is rapid, the deep, narrow valleys which abound may be bridged over by a large mass of rock which is carried from the mountain side into the valley (figure 10). Several examples of this sort are discussed by Früh. Bridges of this type, in daily use by foot passengers, span the Tamina Valley, in Switzerland.[27] Such bridges are probably not uncommon in the narrow mountain gorges of this country; but as they are unusually small, it is difficult to learn of their location. The illustration (plate 26, figure 2) from the Big Horn Mountains shows a rather poor example from Wyoming.

[26] E. R. Buckley: Geology of Miller County, Missouri, Bureau of Geology and Mines, vol. 1, series 2, 1903, p. 13.

[27] J. Früh: Naturbrücken, p. 358; also Früh, Nachtrag zu Naturbrücken, 1907, Tafel 1, St. Gallien.

2. *BY A ROCK SEPARATED FROM ONE BANK AND LEANING AGAINST THE OPPOSITE BANK*

A bridge of unusual origin, and one which, as far as known, has no parallel in the United States, is illustrated by the accompanying section (figure 11). This bridge, which spans the gorge of the Emme, in Switzerland, is formed as follows: A rock of about 35 meters in height was

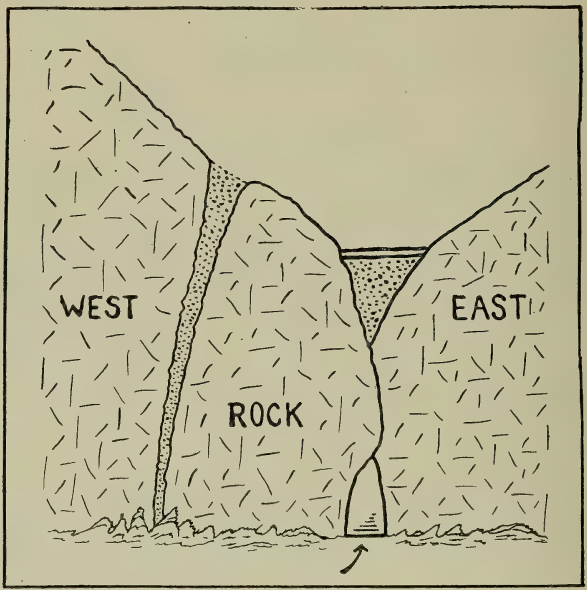

FIGURE 11.—*The "Rebloch" at Schangnau, in the Valley of the Emme, Switzerland*

Redrawn from Kaufmann

separated from the left bank of the gorge, and finally leaned against the wall of the right bank. The wedge-shaped crevice opening upward was then partly filled with debris, and became nicely leveled. The crevice on the left bank formed by the breaking away of the block is also more or less filled with debris.[28]

E. BRIDGES FORMED BY DEPOSITION

1. *BY DEPOSITION OF TRAVERTINE*

The only case of a valley of erosion spanned by a travertine deposit reported from North America occurs near the little Mormon village of Pine, about 90 miles south of Flagstaff, Arizona, and can be reached by a

[28] J. Früh: Ibid., p. 361.

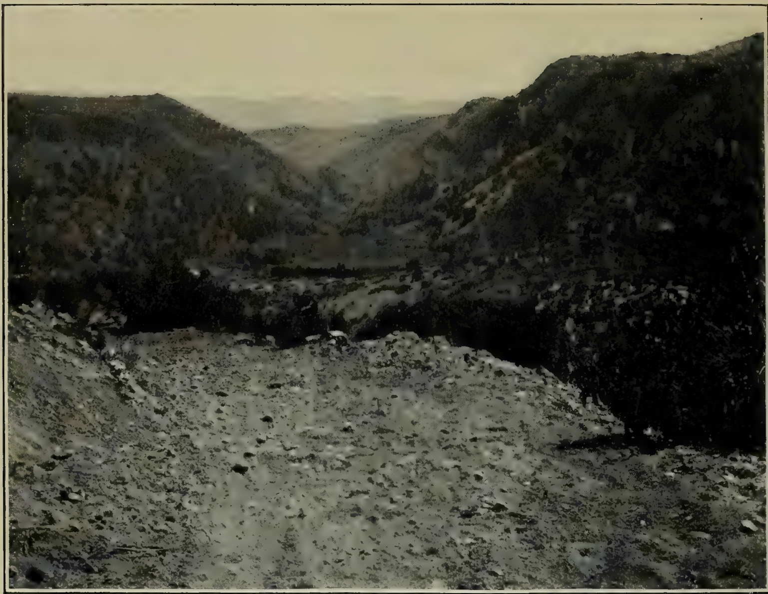

FIGURE 1.—VIEW OF THE VALLEY OF PINE CREEK, ARIZONA

Showing the flat valley floor composed of travertine. The top of the bridge is at the far end (south) of the travertine floor. The springs which have supplied the lime are on the left. (See also plate 28, figures 1 and 2.)

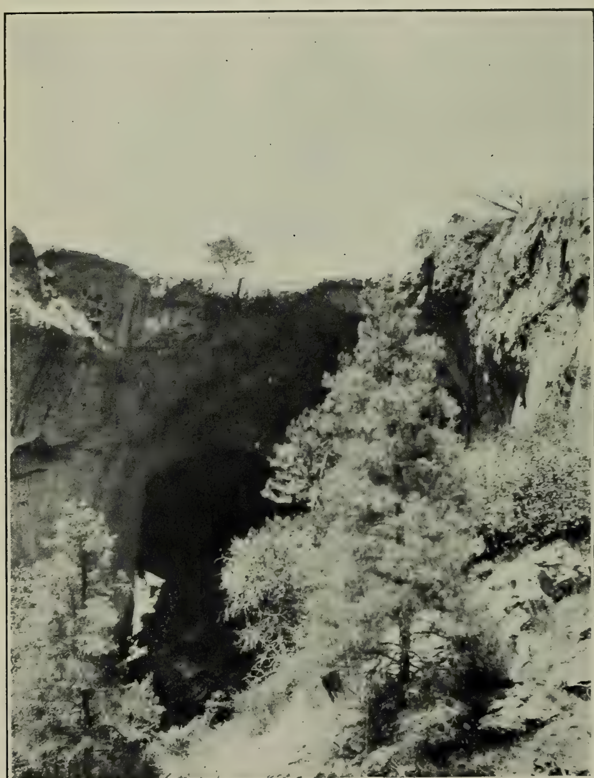

FIGURE 2.—THE TRAVERTINE NATURAL BRIDGE, NEAR PINE, ARIZONA, FROM THE SOUTH

(See also plate 28, figures 1 and 2)

ILLUSTRATIONS OF NATURAL ROCK BRIDGES

horseback journey of three days. Not only is the bridge unique in respect to its origin, but is, moreover, one of the most beautiful natural bridges in the United States, and, with the exception of those in San Juan County, Utah, one of the largest. As one journeys south from Flagstaff through the forest reserve he passes for miles over a lava plateau on which, with the exception of pine and cedar trees, there is little vegetation; when, then, the brilliant green of the irrigated, travertine-filled valley above the natural bridge comes into view, its beauty seems unusual (plate 27, figure 1). The vertical distance from the top of the bridge (plate 27, figure 2) to the creek bed is about 128 feet on the north and 150 feet on the south end. The opening beneath the bridge averages about 140 feet in width, and the length, at the narrowest place, approximately 400 feet. The thickness of the arch is approximately 75 feet, leaving the

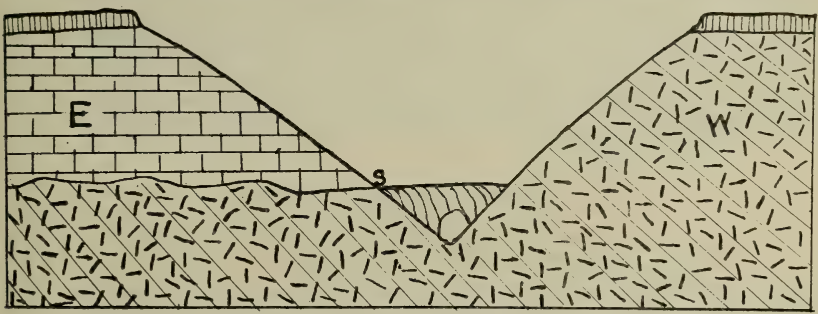

FIGURE 12.—*Diagrammatic Cross-section across Pine Creek, Arizona*

To show the geological relationships. The underlying rock is red porphyry, that immediately overlying is sandstone and limestone, and the capping rock is lava. (See also plates 27 and 28.)

height of the opening beneath the arch between 60 and 70 feet. The altitude of the bridge above the sealevel is approximately 4,700 feet. The origin of the bridge is as follows: Several large springs that flow into the valley from the east side contain lime in solution, which, upon evaporation or loss of carbon dioxide, is deposited as travertine (figure 12). For many years these springs have been depositing travertine in an old valley of erosion cut into red porphyry. As a result of this, an almost level floor of travertine of approximately the same height as the springs increased in width toward the west, filling the valley until it has forced the stream against the porphyry wall on the west side. In one place the travertine was strong enough to support itself, until it was built over the stream to the opposite side of the valley, thus forming a natural bridge. As will be seen from the illustration (plate 28, figure 2), the rock of which the bridge is composed is stalactitic in structure and quite compact. Beneath the arch (plate 28, figure 1) of the bridge are several caves of considerable extent, from the roof of which hang stalactites and from the floor of which stalagmites arise. These caves are reached from below by ladders which have been erected by Mr. Goodfellow, the owner of the bridge.

The extent of the terrace above, and including the bridge, is about 25 acres, and is covered with a good soil which is irrigated from the springs and produces abundant crops of fruit and alfalfa. A small portion of the north end of the cultivated tract is apparently not underlaid with travertine, but is formed by sediment carried in by a small stream. This may, however, also be underlaid by travertine. Travertine terraces, such as that of the natural bridge, also occur in Fossil Creek and Beaver Dam Creek, on the road between Pine and Camp Verde and Flagstaff. No natural bridge, however, has been built in either of these valleys.

The natural bridge of Papigno,[29] east of Terne, is, according to Keller, of this origin. Another bridge near Hierapolis, in Asiatic Turkey; another at Mesquitin, between Tunis and Constantine, in Africa, but which is now said to have fallen, are said to be of this origin.[30] Two travertine bridges are also reported from Chile which span a gorge of the Rio Maipo.

2. *BY SNOW AND AVALANCHES*

Snow and avalanche bridges should be mentioned here, since they are strictly natural bridges.

Conclusions

It will be seen from an analysis of the above—

(1) That natural bridges occur in glaciated as well as unglaciated regions, and that the former, at least, have required a short time, geologically speaking, for their formation.

(2) That they must necessarily be short-lived structures, the life depending upon several factors—the character and composition of the rock, the climatic conditions, etcetera. The North Adams bridge, for example, is a postglacial structure which was evidently formed during the later half of postglacial time, judging from the width of the gorge above and below the bridge.

(3) That they are formed of various materials—limestone, sandstone, marble, gypsum, conglomerate, marl, clay, shale, schist, and lava.

(4) That they fall into at least five well marked divisions, some of which have several subdivisions.

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[29] Pet. Mitt., 1881, pp. 329-330, quoted by Früh, p. 362.

[30] Güssfelt, as quoted by Früh. Ibid., p. 363.

FIGURE 1.—SIZE AND CHARACTER OF THE OPENING UNDER THE ARCH OF THE NATURAL BRIDGE NEAR PINE, ARIZONA

The ladders lead to a cave which is situated near the arch of the bridge. Height, about 75 feet to underside of arch

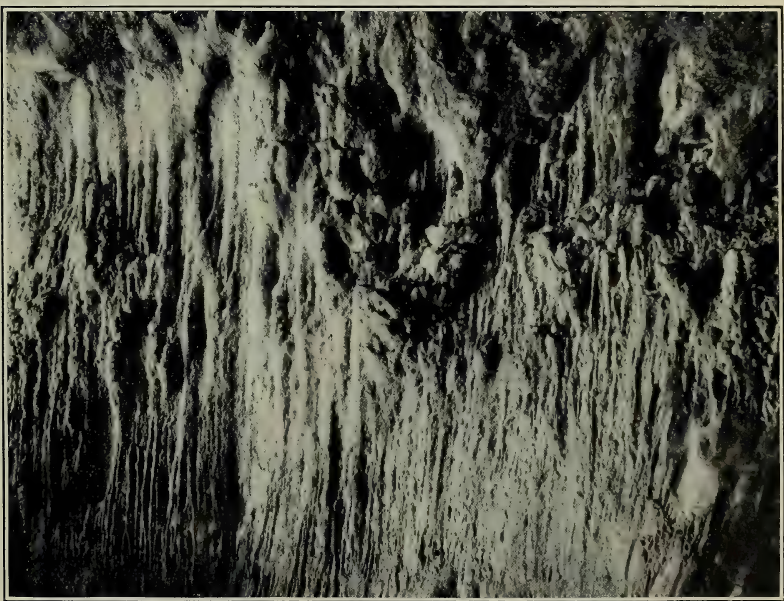

FIGURE 2.—CHARACTER OF THE TRAVERTINE OF THE NATURAL BRIDGE NEAR PINE, ARIZONA

(See also plate 27, figure 2)

ILLUSTRATIONS OF NATURAL ROCK BRIDGES

(5) That it is unsafe to make a definite statement as to the origin of a natural bridge, even when the rock and topography are known, without a careful study in the field.

(6) As concerns the stage of erosion, it may be said in general that they may occur in all stages from youth to advanced maturity or early old age.

If natural bridges were to be classified according to the stage of erosion, it would be found that (*a*) those formed by gravity and by deposition are likely to be found in early stages of valley erosion; (*b*) those initiated by solution, as in C 1, are more likely to occur in the youthful portion of a valley, or, as in C 2, in an advanced stage of the erosion of a region; (*c*) those formed by the perforation of the neck of an incised meander are likely to occur in a submature stage of valley development, either in a new cycle following an advanced stage of a previous cycle or in a more resistant stratum upon which the stream meandered temporarily; (*d*) those formed by pot-hole action may occur in any stage between youth and advanced maturity, and that (*e*) sea erosion bridges are more likely to occur only in rather early energetic stages of sea erosion.

Catalog of North American Natural Bridges

The following is a catalog of North American natural bridges, their location, and the character of rock of which they are composed:

Alabama.—A bridge composed of conglomerate (millstone grit) is reported from Marion County.

Arizona.—(1) The travertine bridge near Pine.
(2) Bridge formed of a petrified log near Adamana.
(3) A bridge near the New Mexico line reported by J. Gardiner, Jr.[31]

Canada.—The limestone bridge across the Kicking Horse River near Field, British Columbia.

California.—(1) The Santa Cruz wave-cut bridge composed of shale.
(2) A bridge across Volcano Creek, a tributary of the Kern in the Sierras.

Florida.—A number of bridges occur in the limestone of this State, of which four are described in this paper.

Indiana.—A sandstone (?) bridge near Attica.

Iowa.—Limestone bridges in Jackson County.

Kansas.—Two gypsum bridges are described in volume v, 1899, page 73, plates 26, 27, of the Kansas Geological Survey. The best of these

[31] Science, vol. 6, 1885, p. 67.

spans Bear Creek, south of Sun City, the height of which is 47 feet in the highest place and the width of the span 35 feet. The origin is not clear from the description.

Kentucky.—Sandstone bridges in Powell and Wolfe counties.

Massachusetts.—The North Adams marble bridge.

Missouri.—Limestone bridges in Miller and Green counties.

New York.—Bridges in Jefferson County composed of Black River limestone.

Oklahoma.—"Natural arch" of limestone, 15 miles southeast of McAlester. Bridges in the Gypsum Hills, in western Oklahoma.

South Dakota.—(1) The sandstone bridge near Buffalo Gap.
(2) A clay bridge spanning Porcupine Creek.
(3) The Big Bad Lands sandstone bridge.

Tennessee.—The sandstone bridge on Lookout Mountain.

Utah.—The four great sandstone bridges of San Juan County.

Virginia.—The great limestone bridge across Cedar Creek.

Vermont.—The schist bridge across the Lamoille River and one other.

Wyoming.—(1) The sandstone bridge spanning Le Perle Creek, in Converse County.
(2) The lava bridge in Yellowstone National Park.
(3) A bridge across Rio Piedra, Wyoming (?).

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ALASKAN EARTHQUAKES OF 1899[1]

BY LAWRENCE MARTIN

(Presented in abstract before the Society December 29, 1909)

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[1] The field observations upon which this paper is partly based were made in the summer of 1905, in connection with a general geological study of the Yakutat Bay region by a U. S. Geological Survey party under the direction of Prof. R. S. Tarr. A grant of money, obtained through the assistance of the American Geographical Society of New York, made it possible for the author to accompany this party as special assistant in physiography and glacial geology.

The office work upon which this paper is more largely based was done during the winters of 1906-8, at the University of Wisconsin, in connection with the preparation of a U. S. Geological Survey professional paper by R. S. Tarr and the author, dealing with these earthquakes and now in preparation.

Acknowledgment is made to H. P. Ritter and R. D. Oldham for the loan of manuscript notes, to H. F. Reid and the U. S. Coast and Geodetic Survey for newspaper clippings, to many seismologists for data, to many persons in Alaska and Canada for replies to earthquake circulars, and to R. S. Tarr and G. K. Gilbert for suggestions regarding the subject-matter of this paper.

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Introductory

THE EARTHQUAKES AND THEIR RESULTS

The severe earthquakes in the Yakutat Bay region, Alaska, in September, 1899, were accompanied by faulting, tilting and warping, by changes of level along the coast, and by glacial oscillations, some of which are still in progress. These have already been described.[2] The earthquakes themselves, however, were only briefly referred to in the reports published. It is the purpose of the present paper to describe these earthquakes.

They lasted 27 days—September 3 to 29, 1899—and included four or five world-shaking disturbances and hundreds of minor shocks. During four weeks there was almost constant palpitation of this part of the earth's crust. The shocks were most severe on September 3, 10, and 23, and were great on the 15th, 17th, 26th, and 29th (figure 6). On the 10th there were over 50 small shocks and two world-shaking disturbances. The greatest faulting took place on September 10, not September 12, as Dr. G. K. Gilbert[3] inferred from an erroneous newspaper report, and probably not September 15, as stated by Comte F. de Montessus de Ballore.[4]

Seismographs and magnetographs in Canada, Mexico, British Isles, Belgium, France, Netherlands, Spain, Germany, Italy, Austria, Russia,

[2] R. S. Tarr and Lawrence Martin: Recent change of level in Alaska. Science, N. S., vol. xxii, 1905, pp. 879-880; Bull. Geol. Soc. Am., vol. 17, 1906, pp. 29-64; Geographical Journal, vol. xxviii, 1906, pp. 30-42.

R. S. Tarr: Recent advance of glaciers in the Yakutat Bay region, Alaska. Bull. Geol. Soc. Am., vol. 18, 1907, pp. 257-286.

Lawrence Martin: Possible oblique minor faulting in Alaska. Economic Geology, vol. ii, 1907, pp. 576-579.

[3] Harriman Alaska Expedition, vol. iii, 1903, p. 23.

[4] La Science Seismologique, Paris, 1907, pp. 31 and 415.

Argentina, India, Japan, Java, Mauritius, and South Africa (figure 6) recorded these shocks, several of which equalled, and one (September 10) far surpassed, the 1906 California earthquake in duration and amplitude. In this wilderness portion of Alaska there was no serious property damage and no recorded loss of life.

FIGURE 1.—*Areas shaken by five great Earthquakes in North America*

Several earthquakes in Jamaica, Mexico, and New England not shown. Maximum areas of New Madrid, Sonora, and Yakutat Bay earthquakes probably much greater, but extreme observations of weak shocks not obtainable in wilderness areas surrounding these three epicentra, as was done for Charleston and California. Minimum area of Yakutat Bay shock of September 10, 1899, shown.

The phenomena accompanying the shocks were observed at distances of 5 to 730 miles, and perhaps raised water waves on Lake Chelan, in Washington, over 1,200 miles away. The minimum land area shaken was 216,300 square miles (figure 1), the land and water area being

400,000 to 500,000 square miles, while distant observations suggest that the shocks may have been sensible over 1,539,000 square miles. The reliable time records, aside from seismograms, are meager but decisive. The shocks were tectonic and attendant upon renewed earth movement accompanying mountain growth.

LOCATION OF AREA

These earthquakes seem to have originated in or near Yakutat Bay, which lies close to the bend of the Saint Elias-Chugach coast range, near

FIGURE 2.—*Map of Alaska (after Brooks)*

Showing relation of mountain axes to earthquake origin in Yakutat Bay

latitude 140 degrees west and longitude 60 degrees north. Figure 2 shows the general location of the Yakutat Bay region as well as the mountain axes in Alaska to which these shocks are related. The Chugach Mountains average 6,000 to 7,000 feet in height, the Saint Elias Range 10,000 to 19,000 feet.

Among the Alaskan towns existing in 1899 Skagway lies 150 miles east of Yakutat Bay, Juneau and Sitka between 200 and 250 miles southeast, and Valdez 250 miles northwest. Glacier Bay is 150 miles east of Yakutat Bay. The Wrangell Mountains, including Mount Wrangell and other active volcanoes, extend parellel to the Saint Elias Range and northwest of it, and from them the Copper River flows southward, crossing the Chugach Mountains and entering the Pacific about 200 miles west of Yakutat Bay. The Alsek River flows southward from the interior of Alaska, entering the Pacific about 60 miles east of Yakutat Bay. The White River and the Tanana, headwaters of the Yukon from the Saint Elias and Wrangell Mountains, flow northward.

TOPOGRAPHY AND GEOLOGY OF THE EARTHQUAKE ORIGIN[5]

The three topographic features near Yakutat, around which was the earthquake origin, are: (1) the Yakutat foreland, a glacial coastal plain less than 250 feet above sealevel; (2) the foothills, rising from 3,000 to 4,550 feet, and (3) the Saint Elias Range, 10,000 to 19,000 feet high. Yakutat Bay, a fiord shaped like a bent arm, consists (figure 3) of (*a*) a broad outer bay in the foreland; (*b*) Disenchantment Bay, a deep fiord in the foothills and mountains, and (*c*) Russell Fiord, partly in the mountains, partly in the foothills, and partly in the foreland. A piedmont ice-sheet, the Malaspina glacier, covers the foreland on the west side of Yakutat Bay, and there are extensive alpine glaciers entering the fiords and mountain valleys and supplied from the snowfields, which cover everything above 3,000 feet where slopes permit. The fiords are chiefly the work of glacial erosion.

The geology of this area of the earthquake origin includes rocks of at least four different ages: (1) Paleozoic or older intrusive and metamorphic rocks; (2) the Yakutat group of sediments, perhaps Mesozoic; (3) the Tertiary coal-bearing group, and (4) the Quaternary glacial and terrestrial accumulations. The Quaternary formations cover the Yakutat foreland and form valley deposits in the mountains. The Tertiary includes an exceedingly small area at the base of the foothills west of Yakutat Bay. The Yakutat group includes all the foothill region and part of the mountains. A northwest to southeast line extending through the northwest arm of Russell Fiord (figure 3) separates the Yakutat group from the metamorphic and igneous older group of rocks. This is an old fault-line, one of those along which renewed movement caused the 1899 earthquakes, particularly that of September 10. The prospectors who experienced these earthquakes from a camp near the junction of Disenchantment Bay and Russell Fiord (figure 3) were, therefore, right on a fault-line. Another old fault separates the Tertiary coal-bearing group from the Yakutat group. A third old fault, inferred by I. C. Russell in 1890, on the basis of topographic form,[6] separates the

[5] Fully described in U. S. Geological Survey Professional Paper no. 64, 1909.

[6] National Geographic Magazine, vol. 3, 1891, p. 57.

Yakutat foreland from the foothills. Along each of these three older faults and several others, there was renewed movement during the 1899 earthquakes.

OBSERVERS OF THE EARTHQUAKES

The observers of the earthquakes include eight prospectors who were at the junction of Disenchantment Bay and Russell Fiord, tributaries to Yakutat Bay, during the most severe shocks; a few whites at Yakutat village, at the entrance of the bay; natives at Yakutat and at Dry Bay, near the mouth of Alsek River, to the east; the captain of a vessel at Yakataga, 100 miles to the west; prospectors at Controller Bay; a Coast and Geodetic Survey party at Cape Whitshed, at the mouth of Copper River; army officers in the Chugach and Wrangell Mountains; cannery employees in Glacier Bay; telegraph operators along the Klondike trail; people living at Skagway, Juneau, Sitka, Valdez, etcetera, and prospectors, missionaries, United States and Canadian government officials, and others in various parts of the 216,000 square miles of wilderness within which the shocks are known to have been felt.

These persons have been corresponded with through a series of 600 earthquake circulars, which were sent in 1907-1908 to the region disturbed, and their observations have been carefully studied.

OBSERVATIONS BY GEOLOGISTS

The only geologists who are known to have observed these earthquakes are Mr. Oscar Rohn, the geologist accompanying Captain Abercrombie's U. S. Army Expedition, who was in the Wrangell Mountains, 170 miles northwest of Yakutat Bay; Mr. A. H. Brooks, of the U. S. Geological Survey, who was near the Tanana River, 250 miles northwest of Yakutat Bay; Prof. J. C. Gwillem, of the Geological Survey of Canada, who was near Atlin Lake, 215 miles southeast of Yakutat Bay, and Mr. F. C. Schrader, of the U. S. Geological Survey, who was on the Koyukuk River, 670 miles northwest of Yakutat Bay. The Harriman Expedition had left Yakutat Bay on the return trip about three weeks before the earthquakes.

CONTEMPORARY DESCRIPTIONS

Descriptions of these earthquakes first appeared in the newspapers. Over fifty such accounts have come to the writer's attention, including items in daily and weekly papers in Alaska, in the United States and Canada, and in Europe. Magazines also referred to the earthquakes briefly; for example, the National Geographic Magazine,[7] the Scientific

[7] Vol. 10, October, 1899, p. 421.

American,[8] and Current Literature.[9] The Governor of Alaska, the Commissioner of Education, the commanders of vessels, United States Army officers, Coast Survey engineers, Weather Bureau observers, postmasters, many Canadian officials, as well as numerous prospectors, missionaries, and others, made notes concerning these earthquakes and referred to them briefly in their reports.

STUDY BY SEISMOLOGISTS

The delicate tremors which traversed the rocks of the earth's crust were recorded by seismographs in practically every observatory in the world where such instruments were then installed. Many magnetographs also recorded them. Several seismologists have given special attention to the records made by this group of earthquakes and specific mention will be made later of the studies by Prof. John Milne, Dr. F. Omori, Dr. R. D. Oldham, several Italian seismologists, and others who knew of the location, time of origin, etcetera, of these earthquakes long before the faulting, the 47-foot uplift, and the glacial oscillations which accompanied or resulted from these shocks were known.

PLAN OF PRESENTATION

The observations in Alaska will be described first of all, the shocks of September 3, those of September 10, and those of September 11 to 29 being presented in order. The seismograph records will then be described, the time records discussed, the disturbed area shown, and the earthquake series will be briefly compared with other great seismic disturbances in Alaska, North America, and the world in general. In conclusion, the relationships of these earthquakes to life will be brought out.

Observations in Alaska

EARTHQUAKE OF SEPTEMBER 3, 1899

List of localities.—The first shock in this series (unless possibly the avalanches heard near the headwaters of the White and Tanana rivers at 8 p. m. on August 27, 1899, were due to an earlier shock on the north side of the mountains[10]) occurred on September 3, at 3h. 3m. 28s., mean local time at Yakutat (or September 4, at 0h. 21m. 40s., Greenwich mean time). The fact that September 3 was the first Sunday in Sep-

[8] Vol. lxxxi, December 23, 1899, pp. 405-406.

[9] Vol. xxvii, February, 1900, p. 123.

[10] Journal of A. H. Brooks for 1899; Seattle Post-Intelligencer, September 23, 1899; Victoria Semi-Weekly Colonist, September 25, 1899; Seattle Weekly Times, October 4, 1899.

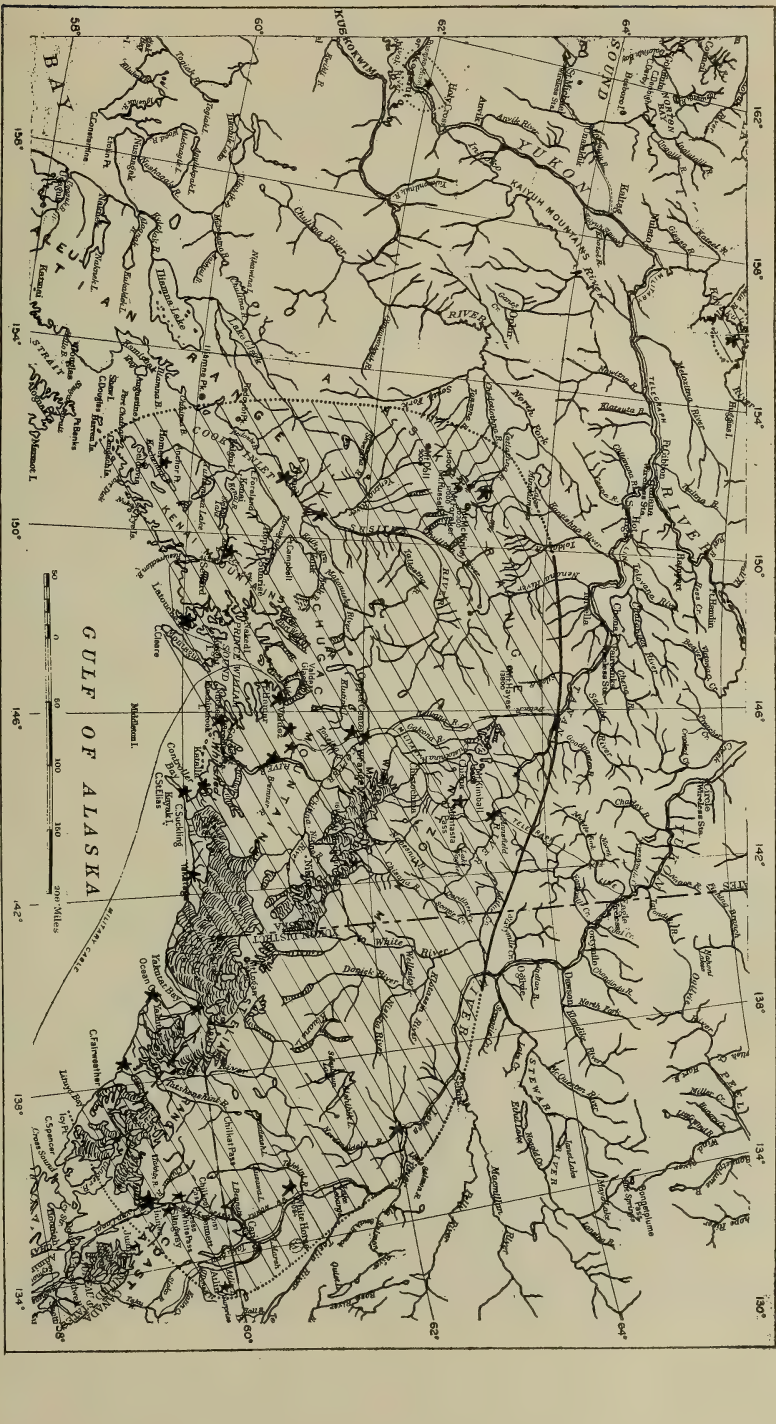

FIGURE 3.—*Map of Part of Alaska*

Showing minimum area within which Yakutat Bay earthquake of September 3, 1899, was felt. Detached areas of shocks on Koyukuk and Yukon rivers. Stars at places of known observations.

tember has simplified collecting the record. It is known to have been felt at the following places (figure 3):

Places.	Location with respect to Yakutat Bay.	Observers.
Disenchantment Bay....	In Yakutat Bay..........	J. Bullman, L. A. Cox, S. Cox, A. Flenner, J. D. Fults, Jr., A. Johnson, T. Smith, and D. Stevens.
Yakutat Village....	Mouth of Yakutat Bay...	C. E. Hill, R. W. Beasley, Mrs. Esther Early, Albin Johnson, and others.
Dry Bay Village	60 miles east of Yakutat...	Dry Bay natives.
Dyea..................	150 miles east-southeast...	A. J. Walker, J. R. Beegle, and others.
Haines Mission	160 miles east-southeast...	Prospectors.
Skagway	160 miles east southeast..	F. S. Williams and others.
Whitehorse.............	170 miles northeast.......	G. S. Fleming.
Tantalus	190 miles northeast.......	Northwest mounted police.
Surprise Lake...........	240 miles east............	John Bimms.
Pacific Ocean	West of Yakutat.........	
Yakataga...............	100 miles west of Yakutat.	B. Durkey, S. E. Doverspike.
Katalla.................	170 miles west	C. W. Chamberlin.
Cape Whitshed	220 miles west-northwest	H. P. Ritter, E. B. Latham, and others.
Chugach Mountains.....	210 miles northwest......	W. R. Abercrombie.
	240 miles northwest......	W. C. Babcock.
	240 miles northwest......	E. S. Larson.
Valdez	250 miles west-northwest.	L. S. Camicia.
Copper River...........	250 miles northwest.....	J. F. Rice.
	250 miles northwest......	A. N. Powell.
Wrangell Mountains	170 miles northwest by north.	Oscar Rohn.
Nutzotin Mountains.....	250 miles north-northwest.	G. B. Rorer.
Tanana River...........	250 miles north-northwest.	A. H. Brooks, W. J. Peters, and others.
Latouche	295 miles west	E. F. Glenn.
Kenai Lake.............	380 miles west	W. E. Lennox.
Homer..................	430 miles west	George Jammé.
Susitna River...........	390 miles west-northwest.	F. R. Falconer.
Tyonek	410 miles west-northwest.	Prospector.
Alaska Range...........	480 miles northwest	J. S. Herron.
Koyukuk River.	730 miles west-northwest.	F. C. Schrader, T. G. Gerdine, D. C. Witherspoon, and others.
Lower Yukon River.....	730 miles west-northwest.	Rev. N. N. Amcan.

Disenchantment Bay.—The Disenchantment Bay point of observation is within 5 miles of the origin of the great earthquake of September 10, and perhaps the September 3d shock also originated here. Eight prospectors, who were washing the gravels of an alluvial fan between the Hubbard and Variegated glaciers (figure 5) for gold and platinum, experienced the earthquake. They were J. Bullman, L. A. Cox, S. Cox, A.

Flenner, J. P. Fults, Jr., A. Johnson, T. Smith, and D. Stevens. Messrs. Cox and Fults have written newspaper accounts of their experience[11] and Mr. Flenner has described it to the writer. This shock was not severe enough in Disenchantment Bay to throw a man off his feet. This is within the area of indurated rocks.

Yakutat.—At Yakutat village, thirty miles distant, Mr. C. E. Hill, a surveyor; Mr. Beasley, the storekeeper; Rev. Albin Johnson, the missionary, and Mrs. Early, a native woman, have stated[12] that the houses rocked and shook violently, a door swung to and fro and shut with a crash, dishes rattled, a table moved, the trees and flag poles rocked back and forth, and the water crossing a reef in the bay was whipped into a mass of seething foam. It was impossible to stand up without support. The region is one of unconsolidated glacial deposits.

There was a general shivering of the earth and then a long jerk; the vibrations were from two to three seconds in length, coming from the northwest and running southeast, slowly at first and then coming shorter and faster and irregularly until they had lasted about 5 minutes. There were slight tremors the rest of the day.

Dry Bay.—At the native settlement at Dry Bay, near the mouth of Alsek River, 60 miles east of Yakutat, the shock was so severe that men were unable to stand.

Lynn Canal.—At Dyea, 150 miles east of Yakutat, A. J. Walker and J. R. Beegle, of the United States customs service, report that the shocks were severe enough to cause lamps to swing, doors and windows to rattle, water to spill from dishes, and piles of freight on wharves to be overturned. Earth-waves traversed the sand flat on which Dyea stands, making people dizzy and causing difficulty in walking.

At Haines Mission, south of Dyea, the shocks were accompanied by the moving of furniture, the swaying of trees, rolling of logs, difficulty in walking, and by cracking of the ground.[13]

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[11] L. A. Cox: Sitka Alaskan, October 14, 1899.

J. P. Fults, Jr.: The Seattle Daily Times, September 28, 1899; New York Sun, September 29, 1899.

[12] C. E. Hill: Seattle Post-Intelligencer, September 23, 1899; San Francisco Examiner, clipping dated Seattle, September 21, 1899; Toronto World, September 25, 1899.

The statements from Mr. Beasley, Rev. Mr. Johnson, and Mrs. Early are from replies to the earthquake circulars and, in the case of Mr. Beasley, from conversations with the writer. In succeeding pages much information regarding earthquake observations in Alaska is quoted. In cases where newspaper articles, official reports, diaries, etcetera, are not cited the information was obtained from the earthquake circulars sent out or from interviews with the observer. Exact quotations or abstracts have been made in most cases, although the quotation-marks have not usually been inserted in this text.

[13] San Francisco Chronicle, September 22, 1899; same, dispatch dated Tacoma, September 9, 1899.

At Skagway, 160 miles east of Yakutat, the shock of September 3 caused buildings and telephone poles to rock from north to south for 3¾ minutes,[14] at 3.17 p. m. Pools of water sloshed about in the streets and beer splashed out of vats in the brewery. The shock lasted long enough for F. S. Williams, the deputy collector of customs, to run from the second floor to the street and wait for the shocks to end. It made people stumble while walking and cracked the putty around large plate-glass windows. A small water-wave was reported in Lynn Canal.

Klondike Trail.—At Whitehorse, 170 miles northeast of Yakutat, in Yukon Territory, Mr. G. S. Fleming, the government telegrapher, felt a slight shock at 3 p. m., lasting 30 or 40 seconds. His dog crouched in terror at the beginning of the tremor and ran home whining.

At Tantalus (Carmacks), a station of the Royal Northwest Mounted Police, 190 miles northeast of Yakutat, the post diary records that a slight shock of earthquake was felt during the afternoon.

At many other points on the trail to the Klondike district this shock was also observed.[15]

Canadian Coast Range.—In the Surprise Lake district, about 240 miles east of Yakutat, John Bimms experienced violent earth tremblings on September 3.[16] Dust from distant mountains suggested smoking volcanoes, but may have been due to avalanches. After-shocks occurred occasionally until September 7.

Pacific Ocean west of Yakutat.—Three different vessels report severe storms or other exceptional conditions at sea west of Yakutat, near Kodiak, etcetera, on September 3. The newspapers suggest a connection between the earthquake and the storms.[17] There seems no good reason for such association, as no evidences of the earthquakes were observed on these vessels.

Yakataga and Controller Bay.—At Yakataga, 100 miles west of Yakutat, S. E. Doverspike, a prospector, states that treetops snapped and earth-waves were felt, the ocean beach was raised three feet, and there were 48 shocks during the ensuing six hours. Captain Durkee, of the schooner *Bellingham*, which was anchored off Yakataga, says the first shock was heavy and continued by shocks every ten to fifteen minutes; avalanches were seen; a current ran offshore at the rate of 3 or 4 miles

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[14] San Francisco Chronicle, September 10, 1899; Seattle Weekly Times, September 27, 1899; New York Tribune, September 12, 1899; Chicago Tribune, September 12, 1899.

[15] New York Daily Tribune, September 12, 1899; Chicago Daily Tribune, September 12, 1899.

[16] San Francisco Chronicle, October 5, 1899.

[17] New York Evening Post, September 26, 1899; Seattle Weekly Times, October 4, 1899.

an hour, and the tide only rose subsequently to half the height indicated by the tide tables, evidently because of the same uplift of the shoreline observed by Mr. Doverspike. There was a roar and the schooner trembled.

At Kayak Island and Katalla, on Controller Bay, 170 miles west of Yakutat, the shocks were also felt and there were great avalanches[18] and dust clouds.

Cape Whitshed.—At the Coast and Geodetic Survey camp west of the Copper River delta, 220 miles west of Yakutat, the shocks observed by H. P. Ritter and E. B. Latham came at 2.40 p. m.[19] These Cape Whitshed observations, at a point whose exact location is known (longitude 145° 54′ 35″ west, latitude 60° 27′ 34″ north) and timed with a good and well-rated chronometer, constitute the most valuable local records of these earthquakes. At only two other points within the shaken area are the time records capable of correction to the standard Greenwich mean time and comparable with the precise times of the seismograph records.

The shock lasted two minutes and was a violent earthquake—direction northeast and southwest—turning floating bottles toward the northeast and throwing the water in a shallow creek out on the bank. The weather was clear, pleasant, and warm. All the movements were apparently lateral and eight or more after-shocks were felt. One at 3h. 22m. 30s. had a few seconds' duration. The time of two light shocks during the afternoon was not noted. A shock at 6h. 45m. lasted ten seconds. Two quite severe shocks came at 7h. 10m., lasting five seconds. Two moderate shocks occurred at 7h. 44m., having a duration of ten seconds, and there were several light ones after this before the Coast Survey observers fell asleep.

Chugach Mountains.—On the Tsina River, 210 miles northwest of Yakutat, at about 2 p. m., Capt. W. R. Abercrombie, of the U. S. Army, felt a succession of shocks which tripped him while walking, caused groves of cottonwoods to wave like wheat, started heavy landslides, and damaged glaciers.

In another part of the Chugach Mountains, 240 miles northwest of Yakutat, Lieut. W. C. Babcock noted the commencement of the earthquakes at 2.28 p. m.[20] The shock began gently, gradually increased in violence until it was impossible to stand erect, and then gradually de-

[18] Dr. C. W. Chamberlin, Seattle Daily Times, September 21, 1899; San Francisco Examiner, dispatch dated Juneau, September 14, 1899.

[19] Annual report of H. S. Pritchett, Superintendent U. S. Coast and Geodetic Survey, Washington, 1901, pp. 78 and 206, and manuscript notes furnished the writer.

[20] Copper River Exploring Expedition. Senate Document 306, 56th Congress, 1st session, 1900, pp. 73-74; Senate Report 1023, 56th Congress, 1st session, 1900, p. 276; extracts from Lieutenant Babcock's diary.

creased; it lasted 1 minute and 10 seconds. The north-south vibrations were so violent that Lieutenant Babcock saw the ground move, cook pails were upset, tall spruces swayed dangerously, and he had a feeling not of fear, but of utter helplessness, accompanied by a slight nausea resembling seasickness. After the shaking eight muffled reports at intervals of about 12 seconds were heard, perhaps from falling avalanches.

In the Tiekel Valley, near Copper River, E. S. Larson says the shocks caused the ground to move, the trees to wave, and woke a man sleeping on the ground. The date was not recorded, but possibly is that of September 3.

At Valdez, 250 miles northwest of Yakutat Bay, Dr. L. S. Camicia, a watch-repairer and optician, reports a strong shock at 2.33 p. m., during which it was impossible to stand on one's feet. Jacob Suter[21] says his chair creaked and swayed, the log cabin shook, and trees rocked. Valdez was not damaged by water waves because the shock came at low tide.

Upper Copper River.—At Copper Center, 250 miles northwest of Yakutat Bay, Mr. J. F. Rice, a quartermaster's clerk of the Copper River Exploring Expedition, was shaken off a stump on which he was standing and making observations at 2 p. m.[22] The ground rocked, trees swayed as in a hurricane, and avalanche roars were heard.

Mr. A. N. Powell, a scout and guide for the same expedition, who was near the junction of the Klutina and Copper rivers, said the earth gave about three swings during 5 seconds, and that there was nothing unusual in the smoking of Mount Wrangell at the time.[23]

Wrangell Mountains.—Mr. Oscar Rohn, geologist for the Copper River Exploring Expedition, was near the divide of the Nizina and Chisana (Tanana) glaciers, in the Wrangell Mountains. This is 170 miles northwest of Yakutat. The surface of the glacier swayed up and down with a slow undulating movement, violent and persistent enough to cause a touch of nausea. The vibrations were perhaps two or three a minute and the motion approximately northeast and southwest. There were minor rapid after-shocks.[24]

Nutzotin Mountains.—Near Mentasta Pass shocks, presumed to be of this group, were felt by Mr. G. B. Rorer, a prospector. This pass across the Nutzotin Mountains is about 250 miles northwest of Yakutat.

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[21] Seattle Daily Times, September 21, 1899; same, September 29, 1899.

[22] Senate Document 306, 56th Congress, 1st session, Washington, 1900, p. 102; and Senate Report 1023, 56th Congress, 1st session, Washington, 1900, p. 788.

[23] Op. cit., page 132 in Document 306 and page 804 in Report 1023.

[24] Copper River Exploring Expedition. Senate Document 306, 56th Congress, 1st session, Washington, 1900, p. 123; and Senate Report 1023, 56th Congress, 1st session, Washington, 1900, p. 800.

Tanana River.—Messrs. A. H. Brooks, W. J. Peters, and a U. S. Geological Survey party were just north of the Tanana River, near latitude 143 degrees west and longitude 63 degrees north, a little over 250 miles northwest of Yakutat. At 3.30 in the afternoon they heard a series of loud, distant sounds, resembling the sound of blasting or the discharge of heavy artillery, repeated at irregular intervals with varying intensity for five or ten minutes, then seeming gradually to lose their intensity and die away. Similar sounds were heard for about a minute at 8 p. m.[25]

Kenai Mountains.—At Latouche, on the west side of Prince William Sound, 295 miles west of Yakutat, Lieut. E. F. Glenn, of the U. S. Army, reports having his attention attracted to this earthquake by feeling as if he were about to fall.[26]

Near Kenai Lake, 380 miles west of Yakutat, a shock observed by Mr. W. E. Lennox on an unrecorded date in the fall of 1899, perhaps September 3, caused lamps to swing, goods to roll from the shelves of a store, and the ground to sway sufficiently to cause dizziness.

At Homer, Kachemak Bay, 430 miles west of Yakutat, Mr. George Jammé, a mining engineer, felt this September 3d earthquake, which threw him against a drawing table.

Cook Inlet.—At Susitna Station, near the head of Cook Inlet and 390 miles west of Yakutat, the September 3d earthquake was observed by Rev. F. R. Falconer at 2 p. m. The shock seemed gentle, with a wave-like motion.

At Tyonek, on the west coast of Cook Inlet, a severe shock was reported to A. H. Brooks by a prospector, whether on the 3d or 10th of September not being recorded.

Alaska Range.—Northwest of Mount McKinley, in the Alaska Range and 480 miles northwest of Yakutat, near the headwaters of the Kuskokwim River, in latitude 63° 30′ north, longitude 152° 30′ west, Lieut. J. S. Herron, of the U. S. Army, felt the September 3d earthquake at 2 p. m.[27] Another shock was felt at 2.30 p. m. The first shock was very severe and seemed to be right under Lieutenant Herron, lasting five seconds. It shook the ground, caused waves two feet high on a creek, made it difficult to stand without holding on to a tree, and impossible to walk. It was a severe and continual rocking or shaking of the earth and not a gradual movement.

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[25] From the journal of A. H. Brooks, September 3, 1899.

[26] Explorations in and about Cooks Inlet. Senate Report 1023, 56th Congress, 1st session, Washington, 1900, p. 715.

[27] Explorations in Alaska, 1899, War Department, Adjutant General's Office, No. xxxi, Washington, 1901, p. 38; Lieutenant Herron's diary for 1899.

Koyukuk River.—Near latitude 66° north and longitude 156° 15′ west, in the Koyukuk River, a northern tributary of the Yukon, is Treat Island, 670 miles northwest of Yakutat (figure 3). Near here Messrs. F. C. Schrader, T. G. Gerdine, D. C. Witherspoon, and a U. S. Geological Survey party encountered water waves at 2.22 p. m., September 3, in a stretch of river otherwise as calm as a mill-pond. Two of these waves were 1½ to 2 feet high in midstream and rose a foot or more above normal river level upon the banks. They moved rapidly upstream, north-northwest, washing back several hundred yards on very flat shores and leaving pools and patches of water, foam, froth, sticks, and vegetable rubbish. Mr. Schrader photographed the receding waves and the debris.[28] A shock was felt by one of the party, Mr. Baker, on shore and by natives. The water waves at this great distance from the earthquake origin may be ascribed to amplification of weak earth movements in the unconsolidated Pleistocene silts over which the Koyukuk River meanders here.[29]

In the Lisbon earthquake of 1755 the waters of Loch Lomond, in Scotland, at a considerably greater distance than this, were affected by water waves at the proper time.

Lower Yukon River.—At Russian Mission, or Ikogmute (figure 3), near the lower bend of the Yukon River, 730 miles northwest of Yakutat and over 300 miles from the place of observation by Mr. Schrader, a Russian priest, Father N. N. Amcan, felt this shock at 2 p. m. The date was not recorded by him, but it seems certain that it was the September 3d rather than the September 10th shock which he observed, because of the time of observation. It was a heavy shock and lasted long enough for one to run out of doors. The similarity of the unconsolidated Pleistocene silts at this point to those on the Koyukuk suggest the reason for sensible disturbances at this great distance from Yakutat Bay. This is the most remote point from the origin at which the earthquake shocks were sensible except to delicate instruments.

Résumé of September 3d earthquake.—This earthquake is known to have been felt at over thirty places (figure 3), the more remote of them as much as 730 miles from Yakutat Bay. The phenomena recorded include trembling of the earth, water waves, avalanches, etcetera, difficulty in standing up, and nausea. It is not definitely known where the origin was, but it has hitherto been assumed that it was in Yakutat Bay. The fact that there was probably faulting and uplift of the coast at Yakataga,

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[28] Described in discussion at Geological Society of Washington, April 25, 1906, and in subsequent correspondence.

[29] See plate lx, opposite page 448, 21st Annual Report, U. S. Geological Survey, part ii, 1899-1900.

100 miles west of Yakutat, suggest that the origin of this first shock might have been there. The nearness of Yakataga to the center of disturbance (figure 3) is not regarded as significant, since the centrum theory of earthquakes has been seriously questioned in recent years. More important is the fact that the prospectors in Disenchantment Bay seem to describe this shock as less severe than in the Chugach Mountains, etcetera, although we may be reading this interpretation into their accounts or they may have experienced such severe shocks afterwards (September 10) that the first shock seemed slight to them in contrast. The greater intensity at Yakutat Village than in Disenchantment Bay is doubtless due to the loose, unconsolidated rocks at the former place on Yakutat foreland, where shocks would be more severe than among the metamorphosed rocks of the mountains in Disenchantment Bay. The time records are not conclusive on this question, but the Yakataga origin is quite as possible as that at Yakutat.

After-shocks of the September 3d earthquake.—Light shocks between September 3d and 9th are recorded by Mr. Fults in Disenchantment Bay, Mr. Hill at Yakutat, Mr. Ritter at Cape Whitshed, and others, but no dates or times were recorded.

FIRST EARTHQUAKE ON SEPTEMBER 10, 1899

List of localities.—On Sunday, September 10, the first heavy shock occurred about twenty minutes of eight in the morning.[30] So far as known, it was recorded at the following places; the list is doubtless incomplete, because of the overshadowing violence of the second shock on this day:

Places.	Location with respect to Yakutat Bay.	Observers.
Disenchantment Bay ...	In Yakutat Bay..........	J. Bullman, L. A. Cox, A. Flenner, J. D. Fults, Jr., A. Johnson, T. Smith, and D Stevens.
Yakutat Village.........	Mouth of Yakutat Bay....	C. E. Hill, R. W. Beasley, Albin Johnson, and others.
Copper River delta......	220 miles west-northwest.	H. P. Ritter, E. B. Latham, and others.
Chugach Mountains.....	240 miles northwest......	W. C. Babcock.
Valdez	250 miles west-northwest.	L S. Camicia.
Upper Alsek River......	90 miles east.............	A. E. Acland.
Upper Yukon River.....	190 miles northeast.......	Northwest mounted police.
Skagway................	160 miles east-southeast...	B. F. Shelton and others.
Juneau	220 miles southeast.....	H. H. Folsom and others.

[30] Assuming an origin in Yakutat Bay, this began at 7h. 43m. 13s. (17h. 1m. 30s., Greenwich mean time), if based on distant seismograph records. Mr. Beasley's time record at Yakutat (7.40) agrees closely with this.

Disenchantment Bay.—In Disenchantment Bay this shock was severe enough to throw a man off his feet. There was movement of the ground and low shrubs shook and were bent as if in a strong wind.[31] There were less severe shocks all the forenoon, fifty of which were counted by Mr. Flenner, one of the prospectors.

Yakutat.—R. W. Beasley[32] and C. E. Hill[33] state that the early shock September 10, at Yakutat Village, made the one of the week before pale with insignificance. Lamps swung, trees swayed, houses creaked and groaned, sleeping people were awakened and rushed out of doors without dressing. The shock lasted 3 seconds. Mr. Hill gives the time as 8 a. m., and Mr. Beasley 7.40, the latter being thought correct because it agrees closely with the seismograph records, as does his time record for the heavier shock the same day.

More distant points.—At the Coast Survey camp at Cape Whitshed, on the Copper River delta, Messrs. Ritter and Latham describe the first shock as light but distinct, lasting a few seconds, at 7.43 a. m., local time, at Cape Whitshed (not the first shock). These times were obtained from a good and well-rated chronometer. The earth vibrated. The weather was calm and cloudy, with occasional showers. The after-shocks include one at 8.01; distinct continuous vibrations, lasting over 100 seconds, at 10h. 38m. 34s.; a shock which lasted 15 seconds and caused the camp flagstaff to vibrate violently, at 10h. 53m. 45s.; a shock violent at the beginning and tapering off toward the end, at 10h. 59m. 55s., the vibrations being continuous for 180 seconds and in a northwest-southeast direction, and a shock lasting 30 seconds at 11h. 5m. 5s.

In the Chugach Mountains Lieutenant Babcock felt a slight shock, lasting eight or ten seconds, at 7.08 a. m.; Dr. L. S. Camicia observed it at Valdez at 7 a. m. Ninety miles east of Yakutat, Sergeant A. E. Acland, of the Royal Northwest mounted police, at Dalton House, north of the Saint Elias Range, recorded it at 7 a. m. At another post, Carmacks, on the Yukon River, 190 miles northeast of Yakutat, it was observed at 8.15 a. m. At Skagway, Juneau, and other points observations of this earthquake were also made.

After-shocks, beside the fifty recorded in Disenchantment Bay, include many at Yakutat Village, fifteen or twenty at Dalton House north of the Saint Elias Range, ten or more at Cape Whitshed, five in the Chugach

[31] J. P. Fults, Jr.: Seattle Daily Times, September 28, 1899; New York Sun, September 29, 1899.
L. A. Cox: The Sitka Alaskan, October 14, 1899.

[32] The Sitka Alaskan, September 16, 1899.

[33] San Francisco Examiner, dispatch dated Seattle, September 21, 1899.

Mountains, two at Carmacks on the Yukon, five at Skagway, several at Juneau, etcetera. Of these after-shocks, those at Dalton House, 90 miles northeast of Yakutat Bay, lasted from 5 to 40 seconds; those at Cape Whitshed, 220 miles west of Yakutat, lasted 100 to 180 seconds.

THE GREAT EARTHQUAKE OF SEPTEMBER 10, 1899

General character.—The greatest earthquake of this series began at 12.22 p. m., local solar time, in Disenchantment Bay, near Yakutat, or 21h. 40m. 13s., Greenwich mean time.[34] It is practically certain that this is the shock in association with which the faulting and changes of

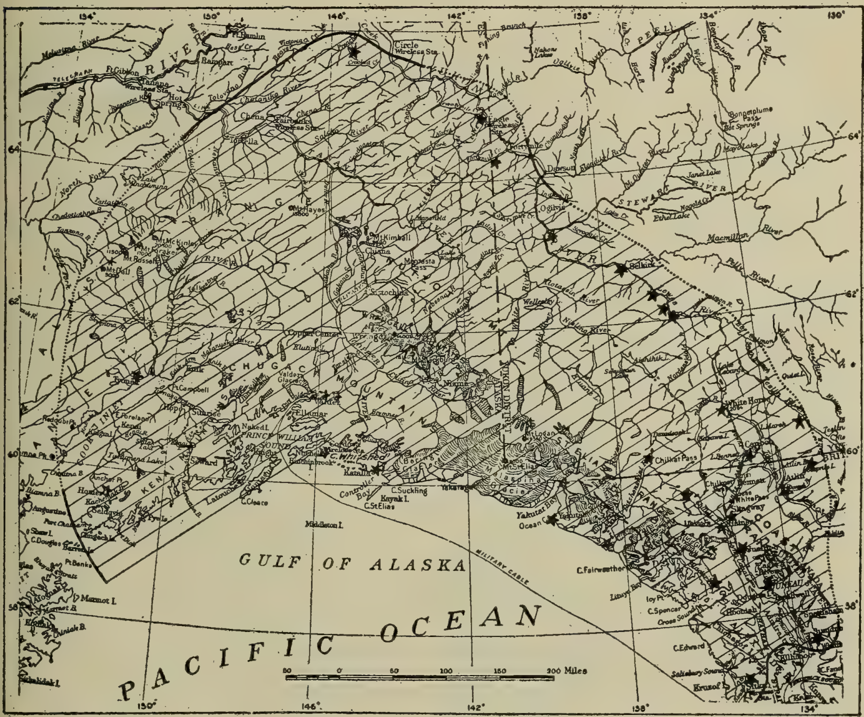

FIGURE 4.—*Map of Part of Alaska*

Showing minimum area within which the great Yakutat Bay earthquake of September 10, 1899, was felt. Stars at places of known observations

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[34] The time of this shock has been variously stated. In earlier papers (Bull. Geol. Soc. Am., vol 17, 1905, p. 31, and Geographical Journal, July, 1906, p. 38) the time has been given as 3 p. m., based on a single statement by a local observer. It has also been stated by men on the ground as 12.15, 12.30, 1.20, 1.30, 1.50, 2 o'clock, etc., their timepieces varying in relation to solar time. The present figure is computed from the Coast Survey observation near the Copper River delta and distant seismograph records, and may be accepted as correct.

level of the coast took place. Everywhere within the sensibly shaken area this is reported as the most severe of the series, and this conclusion is supported by the seismograph records. The origin may be assumed to be near 59° 58′ 20″ north latitude and 139° 33′ west longitude.

List of localities.—So far as known, the shock was felt at the following places (see figure 4):

Places.	Location with respect to Yakutat Bay.	Observers.
Disenchantment Bay	In Yakutat Bay	J. Bullman, L. A. Cox, S. Cox, A. Flenner, J. P. Fults, Jr., A. Johnson, T. Smith, and D. Stevens.
Yakutat Village	Mouth of Yakutat Bay	C. E. Hill, R. W. Beasley, Mrs. Esther Early, Albin Johnson, and others.
Pacific Ocean	West of Yakutat	
Controller Bay	170 miles west of Yakutat.	T. G. White.
Copper River delta	220 miles west-northwest.	H. B. Ritter, E. B. Latham, and others.
Chugach Mountains	240 miles northwest	W. C. Babcock.
Chugach Mountains	250 miles northwest	J. D. Jefferson.
Valdez	250 miles west-northwest.	L. S. Camicia.
Homer	420 miles west of Yakutat	George Jammé.
Cook Inlet	410 miles west-northwest.	E. F. Glenn.
Birch Creek District	430 miles northwest	J. E. Kinnaley.
Eagle	340 miles north-northwest.	W. G. Myers.
Forty Mile District	290 miles north-northwest.	F. Dennison.
Stewart River	240 miles north	Lars Gunderson.
Fort Selkirk	215 miles north	
Five Fingers	200 miles northeast	Telegraph operator.
Tantalus	190 miles north	Northwest mounted police.
Upper Yukon River	180 miles northeast	J. J. McArthur.
Upper Yukon River	190 miles northeast	Northwest mounted police.
Whitehorse	170 miles northeast	G. S. Fleming.
Tagish	180 miles east	Telegraph operator.
Upper Alsek River	90 miles northeast	A. E. Acland.
Upper Alsek River	115 miles east	Prospectors.
Dry Bay	60 miles southeast	Charles Johnson.
Glacier Bay	150 miles southeast	August Buschmann.
Atlin Lake	215 miles east	J. C. Gwillim.
Atlin District	230 miles east	J. H. Pottinger.
Surprise Lake	240 miles east	John Bimms.
Teslin Lake	275 miles east	G. E. Boulter.
Skagway	160 miles east-southeast	C. L. Andrews, B. F. Shelton, and others.
Berners Bay district	180 miles southeast	H. W. Mellen.
Juneau	220 miles southeast	H. H. Folsom and others.
Sumdum	275 miles southeast	R. V. Rowe.
Sitka	260 miles southeast	P. T. Rowe, Andrew Malakoff, and others.
Lake Chelan, Washington.	1,200 miles southeast of Yakutat Bay. Water waves perhaps due to this earthquake.	Residents of Chelan.

Disenchantment Bay.—In inner Yakutat Bay, near the junction of Russell Fiord and Disenchantment Bay, the great earthquake at noon was felt by the same eight prospectors who were there during the shocks of September 3 and early September 10. The testimony of these men—Messrs. Bullman, the two Coxes, Flenner, Fults, Johnson, Smith, and Stevens—is of great importance, as they were right in the midst of the faulted area on one old fault-line, and consequently at the very origin of the earthquake. Two of them have written accounts of their experience[35] and the author has talked with a third, Mr. Flenner. Their accounts agree well and seem in the main reliable.

They were in two camps (figure 5) on the moraine and alluvial fan of Variegated Glacier near the elbow in Yakutat Bay, where they were engaged in placer mining. They had made a contrivance of suspended hunting knives whose points touched and jingled when the earth trembled. With this they counted 52 shocks on September 10, culminating in the great earthquake at noon.

The shock was so severe that it was impossible to stand and two of the men who were in a tent held on to the pole to keep from being thrown to the ground, while a third fell over a stove in attempting to get outside. The land swayed and undulated and was broken along jagged cracks and moved up and down. This was estimated to have lasted two and a half or three minutes. Numerous fish were killed by the shock. The dam of a lake was broken and a flood washed down on the camp, burying part of it beneath rocky debris. A great water wave, which seemed to be 20 feet high, rushed upon the shore. Some of the men were washed high up on the moraine by this wave. There was a second wave 20 or 30 feet high. Avalanches descended the mountain slopes with deafening roar. The Hubbard Glacier, which is about two miles to the northwest and has a tidal front five miles across, was broken and great quantities of ice discharged into the fiord. A boat was smashed to kindling wood and most of the tents, provisions, bedding, and clothing were lost. A stream was diverted from one course on the alluvial fan, divided, and reunited again.

The men ran to and fro aimlessly, saving a few provisions and blankets, and eventually seeking shelter on the mountain side. They tied themselves to shrubs with strips of clothing and spent a disturbed afternoon and night, harassed by roaring avalanches, swollen streams, rain, occasional earthquakes, and anxiety as to the future. Their position was precarious, for they were cut off from retreat by land by the crevassed

[35] L. A. Cox: The Sitka Alaskan, October 14, 1899.
J. P. Fults, Jr.: Seattle Daily Times, September 28, 1899, and New York Sun, September 29, 1899.

Hubbard and Nunatak glaciers. No one knew of their being here, and for all they knew Yakutat might have been destroyed. One of their boats was smashed and the other washed away, as were all their sluices, and there was no driftwood or any timber large enough to make a raft.

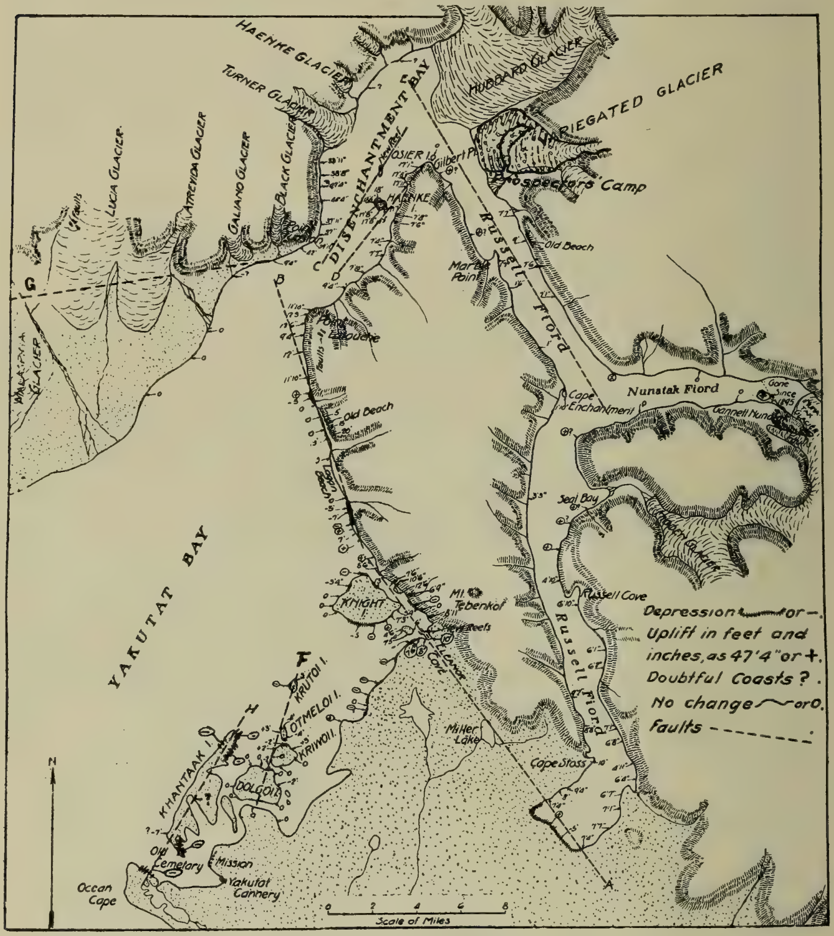

FIGURE 5.—*Faults, Uplifts, and Depressions of Yakutat Bay*

As mapped by Tarr and Martin in 1905 and 1909. It is probable that this faulting took place chiefly during the great earthquake on September 10, 1899

They had no food except 6 pounds of wet corn meal, 3 or 4 pounds of flour, a small piece of bacon, and a few canned goods.

Next day, however, their twelve-foot boat was found lodged among the alders, a damaged native canoe was picked up afloat in the fiord, the scanty provisions were replenished from the abundance of dead fish washed up by the earthquake wave, and the men started for Yakutat Village, 30 miles distant.

Often the boats had to be carried bodily across the compact jam of icebergs, and it was only after several days' hard work that Yakutat was reached.

It was found in 1905 that the earth movement with which these earthquakes were associated was along seven or more fault-lines, involved the tilting and jostling of three or more blocks of the earth's crust in Yakutat Bay. Accompanying this were changes of level of the land including uplifts of 7 to 10 feet on the southeast side of the bay, 40 to 47 feet on the northwest side, as well as the submergence of coasts from 5 to 7 feet. One of the faults bounding these blocks is at least 30 miles long, another is over 17. Eight miles west of the prospectors' camp the coast was uplifted $47\frac{1}{3}$ feet, two miles southeast there was a $7\frac{1}{2}$-foot uplift, while at their camp there was no change of level. The distribution of these faults and changes of level is shown in figure 5. Along faults A, B, E, and F the movement was a renewal of faulting along old faults. Along several of the faults $4\frac{1}{2}$ miles west of the prospectors' camp, new reefs were raised above sealevel. Seventeen miles southeast, near Nunatak Glacier, minor faulting broke a hill into strips, 29 step faults from a few inches to nearly 8 feet high being observed in 1905.

All these phenomena, more fully described elsewhere,[36] might be presumed to have taken place during the great earthquake at noon on September 10, because this is the only shock of this series which is known to have been accompanied by water waves in Disenchantment Bay or at Yakutat Village, and it is inconceivable that such notable faulting, elevation, and submergence could have taken place without great water waves. Dr. H. F. Reid has suggested that weak, unobserved water waves accompanied faulting along faults A and B during the early shock of September 10, and that the movement along faults C, D, E, F, G, and H caused the great earthquake of September 10, the September 3d faulting having been at Yakataga, as suggested above.

The avalanches during this and the other earthquakes of this series resulted in a brief spasmodic advance of the Galiano Glacier between 1899 and 1905,[37] followed by similar advances of the Variegated, Haenke, Atrevida, and Marvine lobe of Malaspina Glacier between 1905 and

[36] R. S. Tarr and Lawrence Martin: Recent changes of level in Alaska. Bull. Geol. Soc. Am., vol. 17, 1906, pp. 29-64, and in a professional paper of the U. S. Geological Survey in preparation.

[37] R. S. Tarr and Lawrence Martin: Glaciers and glaciation of Yakutat Bay, Alaska. Bull. Amer. Geog. Soc., vol. xxxviii, 1906, pp. 152-153.

1906,[38] and of Hidden, Lucia, and Hubbard glaciers between 1906 and 1909.[39]

Yakutat.—At the village of Yakutat, 30 miles from Disenchantment Bay, the great earthquake was observed, and has been described by Mr. Beasley,[40] the storekeeper; Mr. Hill,[41] a surveyor; Rev. Mr. Johnson,[42] the missionary; Mrs. Esther Early, a native woman; W. M. Rock,[43] a prospector, and many other whites and Yakutat natives.

Some of the facts mentioned below are also from correspondence and from conversations. The harbor and settlement at Yakutat is shown in figure 6.

Mr. Beasley states that the great earthquake came at 12.15, agreeing closely with the computed time records. It had a duration of five seconds. All the canned goods on the shelves and all the kettles, pails, and lanterns hanging from nails overhead were shaken to the floor of the store. There were waves in the ground and water waves in the bay.

Mr. Hill states that people were unable to walk or stand without holding to something. The church bell in its tower was rung by the tremors. Three great waves rolled into the bay at intervals of about five minutes, raising the level of the water 15 feet and nearly washing away some of the native houses. Mr. Beasley states that the water rose 8 or 10 feet in as many minutes. Mrs. Early observed that the water ran out a long distance before the coming of the first great wave.

After this shock all the inhabitants of Yakutat except Mr. Beasley lived in tents on the hills above town. There were 247 inhabitants at Yakutat in 1900 and presumably about the same number in 1899.

The residents agree that the old native cemetery on Khantaak Island was partly destroyed by subsidence during this earthquake (figure 6), which was along a fault-line (H, figure 5), as the linear arrangement of subsidence shows. Near Ocean Cape sand vents, or craterlets, developed during this shock, leaving holes 4 or 5 feet deep and scattering sand 6 inches deep over several acres. About ten acres in this vicinity were also affected by fissuring, looking as if plowed by great furrows about 4

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[38] R. S. Tarr: Recent advance of glaciers in the Yakutat Bay region, Alaska. Bull. Geol. Soc. Am., vol. 18, 1907, pp. 257-286; and Professional Paper no. 64, U. S. Geological Survey, 1909.

[39] R. S. Tarr and Lawrence Martin: National Geographic Magazine, vol. xxxi, 1910, pp. 1-54.

Lawrence Martin: Popular Science Monthly, vol. lxxvi, 1910, pp. 293-305.

[40] R. W. Beasley: The Sitka Alaskan, September 16, 1899.

[41] C. E. Hill: Seattle Post-Intelligencer, September 23, 1899; San Francisco Examiner, dispatch dated Seattle, September 21, 1899; Toronto World, September 25, 1899.

[42] Rev. Albin Johnson: Report of Commissioner of Education, 1898-9, vol. 2, p. 1402.

[43] W. M. Rock: Victoria Semi-Weekly Colonist, October 12, 1899.

feet apart and 4 or 5 feet deep. A cloud of dust from an avalanche was seen from a distance.

In 1905 and 1909 we found drowned forests and other evidences of subsidence at a dozen places from 1 to 14 miles from Yakutat Village (figure 6), and the statement that water waves accompanied only this shock at noon September 10 suggests that the subsidence all came in connection with this one great earthquake.

The steamship *Dora* touched at Yakutat on September 12, 1899, and her crew and passengers brought the first news of the earthquake here to

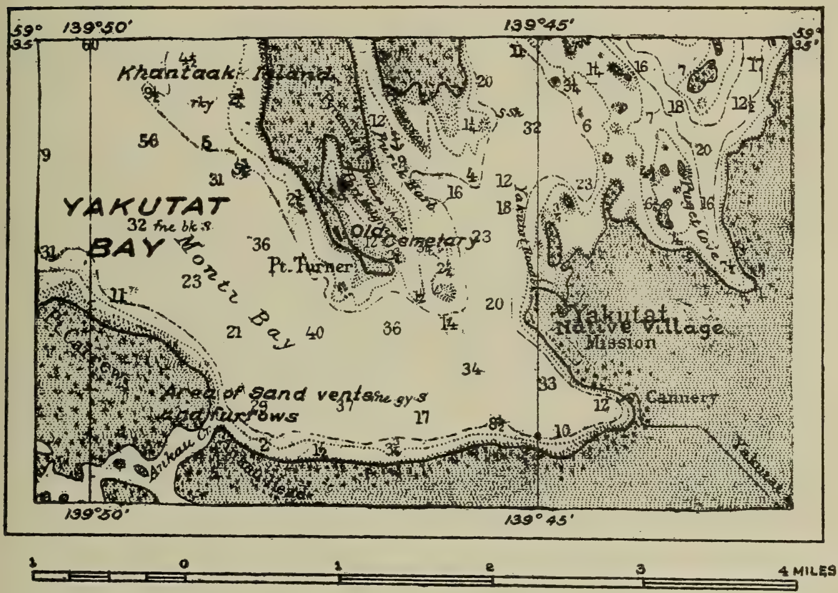

FIGURE 6.—*The Harbor at Yakutat Village*

Where submergence, water waves, and sand vents, or craterlets, developed during the great earthquake of September 10, 1899. Soundings in fathoms (after U. S. Coast and Geodetic Survey).

the outside world.[44] The United States revenue cutter *McCulloch* reached Yakutat on September 17. Capt. W. C. Coulson refers briefly to the earthquakes and to changes in the entrance to the harbor in the log of the vessel. The Governor of Alaska, Mr. Brady, went ashore and learned of the earthquakes, to which he refers incidentally in his annual

[44] Sitka Alaskan, September 16, 1899; San Francisco Examiner, dispatch dated Juneau, September 14, 1899; San Francisco Chronicle, dispatch dated Seattle, September 20, 1899; Seattle Daily Times, September 21, 1899; Butte Weekly Miner, September 21, 1899; New York Daily Tribune, September 21, 1899; same, September 22, 1899; New York Evening Post, September 21, 1899; Toronto Mail and Empire, September 22, 1899.

reports for 1899 and 1900.[45] Rev. Sheldon Jackson, the Commissioner of Education for Alaska, also gathered information regarding the earthquakes, to which he refers briefly in his diary[46] and in a somewhat exaggerated account published by the Associated Press.[47] A newspaper and magazine writer, W. J. Lampton, of the New York Sun, who also happened to be on the revenue cutter, interviewed the prospectors who had experienced the earthquakes in Disenchantment Bay.[48] Some numbers of the crew also described the earthquakes.[49]

Pacific Ocean west of Yakutat.—A severe storm at the time of the September 10 earthquake was felt by the revenue cutter *McCulloch* and was ascribed in the press to this earthquake.[50] Mr. Andrew Brown also experienced a very severe storm at sea between Kodiak and Sitka, on the steamship *Alliance*. No earthquake phenomena are reported, however, and these cases are cited merely to point out that the association by newspapers of these storms with the earthquakes is probably wholly without basis.

Controller Bay.—At Katalla, on Controller Bay, 170 miles west of Yakutat, Mr. T. G. White reports that the shaking was so strong on September 10 that one could not stand. Avalanches fell, trees waved on a calm day, a water wave 4 feet high went up the Bering River. An oil spring is said to have started flowing and oil is reported to have been seen in large amounts afterwards on the surfaces of streams and ponds near Katalla.[51]

Cape Whitshed.—At the Coast and Geodetic Survey camp near the Copper River delta and 220 miles west of Yakutat, Mr. Ritter and Mr. Latham observed the great earthquake at 11h. 58m. 33s. true local time, recorded by a good and well-rated chronometer. It lasted three minutes. There was violent shaking all the time; part of the time one way, then another. It seemed rotary. The top of a 40-foot flagstaff vibrated from 1 to 4 feet, and people had to stand with their heels at least 8 inches apart to keep from falling. It was impossible to stand with the heels together.

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[45] Department of the Interior, Misc. Repts., House Document 5, 56th Congress, 1st session, part ii, p. 29; House Document 5, 56th Congress, 2d session, part ii, p. 25.

[46] Ninth Annual Report on the introduction of domestic reindeer into Alaska. Government Printing Office, Washington, 1900, p. 50.

[47] Sitka Alaskan, September 23, 1899; San Francisco Examiner, September 25, 1899; London Times, September 26, 1899; Victoria Semi-Weekly Colonist, September 28, 1899; Portland Weekly Oregonian, September 29, 1899; Japan Times, Tokio, October 31, 1899.

[48] New York Sun, October 1, 1899.

[49] Seattle Daily Times, September 28, 1899.

[50] Seattle Daily Times, September 28, 1899.

[51] G. C. Martin: Bull. no. 335, U. S. Geological Survey, 1908, p. 117.

The plumb bob kept swinging slightly. There were at least four after-shocks and the earth vibrated practically all day. The after-shocks came at 12h. 7m. 8s., at 5h. 36m. 8s., at 5h. 44m. 2s., and the final one at 5h. 51m. 41s. The last one was stronger than those preceding.

The topographic effects within a radius of 10 to 15 miles of this camp, observed while making soundings and surveying shorelines on the Copper River delta during and after these earthquakes, consisted only of the sliding down of an occasional overhanging tree or soft bank or the soft portion of an overhanging rocky bluff.[52]

Chugach Mountains.—In the Chugach Mountains, 240 miles north-west of Yakutat, Lieutenant Babcock and the army officers building the military trail observed the great earthquake at 10.45 a. m.[53] It lasted a minute and ten seconds. Avalanches probably attended it, for peculiar reports similar to those of the preceding Sunday were heard.

In another part of the Chugach Mountains, about 55 miles east of Valdez Inlet, Mr. J. D. Jefferson, assistant postmaster at Valdez, who was encamped on Fall Creek, saw the trees and mountains swaying. A tent pulled and strained at its ropes. There was a great avalanche. What is described as a sickened feeling came over the observers.

At Valdez Village, still farther west, Dr. L. S. Camicia was so dizzy that he could not stand. A tidal wave 7 feet high came in from the sea.[54] The flagpole and the tops of trees vibrated.[55] Valdez had a population of 315 in 1900 and presumably about the same in 1899.

Kenai Mountains.—At Homer, on the end of a long sand spit in Kachemak Bay, Mr. George Jammé, a mining engineer, observed the great earthquake on September 10 at a point 420 miles west of Yakutat. He had arranged a swinging plumb bob after the shocks of the preceding Sunday, and observed that during this earthquake the bob swung in an ellipse with axes 9 and 17 inches long, the longer extending northwest-southeast.

Cook Inlet.—At Ladds Station, 5 miles north of Tyonek and 410 miles northwest of Yakutat, Lieut. E. F. Glenn, of the U. S. Army, felt the earthquake while eating. It was very severe, lasting long enough for him to walk out of a frame building, and it was perceptible afterward. The building rocked back and forth and every person or animal staggered or reeled.

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[52] Annual Report U. S. Coast and Geodetic Survey, Washington, September, 1901, p. 206.

[53] Diary of Lieutenant Babcock.

[54] Seattle Daily Times, September 29, 1899.

[55] Philipp Glesener: Personal communication.

Upper Yukon Valley.—In the Birch Creek district, west of Circle and about 430 miles northwest of Yakutat, Mr. J. E. Kinnaley felt an earthquake September 11, 1899 (probably September 10), which lasted long enough for one to run 20 feet. The ground seemed to be moving and sinking at the same time. There was a landslide at Pitkas Bar, on Birch Creek. Twenty miles distant, on Independence Creek, the water was thrown out of a sluice-box.

At Eagle, 340 miles north of Yakutat, the U. S. Weather Bureau observer, Judge W. G. Myers, felt the September 10 shock at 12.15 p. m. This is stated to be 141st meridian time, based on observations of the sun every few days. The shock lasted three or four seconds, jarring suspended mercurial barometers against rings at the bottom, beside causing poles to vibrate, lamps to swing, and tin plates on shelves to rattle.

In the Forty-Mile district, 290 miles north of Yakutat, Mr. F. Dennison reports a shaking of the ground observed by a number of prospectors in and near Jack Wade Creek. The exact date in September, 1899, was not recorded, but it may safely be presumed to be the 10th rather than the 3d because of the time of the shock, about noon.

Klondike Trail.—At the mouth of Stewart River, on the Yukon, 240 miles north of Yakutat, Judge Lars Gunderson, United States commissioner, felt very light shocks during the first ten days of September, 1899. People noticed clothes swinging gently from lines inside their houses. Many persons were dizzy.

At Fort Selkirk, where the Lewes and Pelly rivers unite to form the Yukon, and 215 miles north of Yakutat, one of these shocks in September, 1899, is said to have been felt, the date and hour not being recorded.

At Five Fingers rapids in the Lewes River, the Canadian telegraph operator wired to Whitehorse on September 10, shortly after 1.30 p. m., that he had just felt the great earthquake.

The foreman of a party engaged in building a winter trail near Five Fingers rapids relates that they were having lunch near the new telegraph line and had their attention attracted to the earthquake by the violent swaying of the wire and the heaving of the trees. Several men were seized with vertigo and the distant booming sound caused great consternation.

At Tantalus, or Carmacks, near 62° 6′ north latitude and 136° 15′ west longitude, 190 miles north of Yakutat, the earthquake was recorded September 10 in the post diary of the Tantalus detachment, Royal Northwest mounted police, at 11.45 a. m., as a rather severe shock. This time record is probably more nearly correct than that at Five Fingers, near by. Strong after-shocks were felt at 11.55 a. m., at 12.30 p. m., and at 12.45 p. m.

Along the Upper Yukon or Lewes River, near the mouth of Nordenskiold River, 190 miles north of Yakutat, Mr. J. J. McArthur, in charge of the telegraph line, did not feel this earthquake personally, probably because he was travelling on horseback, although his men working on the winter trail did. He did hear an irregular succession of loud detonations like the booming of cannon, and thought it was blasting. It may have been the fall of avalanches. He followed a trail from which his axemen had removed fallen timber that morning and found that trees up to 12 inches in diameter were overturned across the trail by the swaying motion of the earthquake. There was no wind at the time.

At Whitehorse, south of Lake Lebarge and 170 miles northeast of Yakutat, Mr. G. S. Fleming, the government telegrapher, reports that the severe earthquake September 10 came at 1.30 p. m., lasting between 45 and 60 seconds. Windows and dishes rattled; water splashed out of a pail; people rushed out of a log cabin, but had no difficulty in walking. Several waves crossed the river and dust rose from falling river bluffs. The motion of the earth was gradual. H. E. Porter observed trees swaying overhead on a perfectly still noon.

At Tagish, on Lake Bennett, 180 miles east of Yakutat, this shock was also felt and reported by telegraph to Whitehorse, 50 miles northward. The level of Lake Bennett is said to have been disturbed.

At Caribou Crossing, Bennett, White Pass, and various other points on the trails in Yukon Territory between Lake Bennett and the Klondike district, the earthquake was also felt,[56] the information being often indefinite as to date, place, etcetera, or exaggerated in details.

North of Saint Elias Range.—At Dalton House, Yukon Territory, east of the Alsek River, near 60° 6′ 30″ north latitude and 137° 4′ west longitude, about 90 miles northeast of Yakutat Bay, the great earthquake was felt by Sergt. A. E. Acland, of the Royal Northwest mounted police. It came about noon and lasted fully a minute. A log cabin was so severely shaken as to be unsafe; trees and flagpoles vibrated like a snapped whip; water spilled out of the east and west sides of wash dishes and pails; kitchen utensils swung on their nails; plates and cups were shaken off shelves; horses grazing two miles away came home at a gallop, frightened and snorting. There were heavy noises from the southwest, resembling far-away explosions or rumbling of thunder, thought by Mr. Acland to be due to shifting of glaciers in the Alsek Valley, but perhaps caused by avalanches. The motion was a gentle shaking at first, growing gradually more severe and then dying away. The men had to brace their knees in order to keep from falling.

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[56] Victoria Semi-Weekly Colonist, September 25, 1899; Seattle Weekly Times, September 27, 1899; same, October 4, 1899.

At Glacier Camp, on the Dalton trail, north of the Saint Elias Range and 115 miles east of Yakutat, two men were building a cabin, one of whom was shaken off the log he was placing on the wall by the earthquake.

Dry Bay.—At the mouth of the Alsek River, 60 miles southeast of Yakutat, information collected for the writer by Charles Johnson indicates that the Dry Bay natives felt this September 10 earthquake as a much more severe one than that of the preceding Sunday. They were unable to stand up during the heaviest shaking and some of their houses were damaged by the earthquake.

Glacier Bay.—In this inlet, 150 miles southeast of Yakutat and famous as the location of Muir Glacier, the earthquake was observed by Mr. August Buschmann, superintendent of the Bartlett Bay salting station. He observed two shocks, not recording the exact time. They seemed to come from the westward. One lasted ten seconds, the other five seconds. They caused a trunk to move several inches on its casters and empty barrels to fall from beams overhead in the fish-house. An old man, walking up the beach, nearly fell during the earthquake.

The flow of icebergs from Muir Glacier increased many fold, the amount of drift ice in Glacier Bay making navigation for the small cannery steamers very difficult, as Mr. Buschmann observed.

The increase of floating ice and damage to Muir Glacier was noticed at once[57] in Glacier Bay and Icy Straits. It was commented on by the members of the Harriman Expedition,[58] and has been accompanied by a great recession of glaciers. Prof. H. F. Reid has recorded the retreat of Muir and adjacent glaciers.[59] Supt. O. H. Tittmann, of the U. S. Coast and Geodetic Survey, observed the floating ice on July 29, 1900, on the steamship *Queen.* Other vessels attempting to reach Muir Glacier in 1901 and 1902 were turned back by the floating ice in greatly increased amounts. The Muir Glacier receded between 2½ and 3 miles between 1899 and 1903;[60] it continued to retreat through 1906;[61] by 1907 it had receded about 8 miles from its position before the earthquakes in 1899.[62]

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[57] Victoria Semi-Weekly Colonist, October 2 and October 12, 1899; Scientific American, vol. lxxxi, 1899, pp. 405-406.

[58] John Burroughs: Harriman Alaska Expedition, vol. i, p. 89.

G. K. Gilbert: Harriman Alaska Expedition, vol. iii, pp. 23-25; National Geographic Magazine, vol. xiv, 1903, p. 445.

[59] Variations of glaciers. Journal of Geology, vol. ix, 1901, p. 253; x, 1902, p. 317; xi, 1903, p. 287; xii, 1904, pp. 258-260.

[60] C. L. Andrews and W. H. Case: National Geographic Magazine, vol. xiv, 1903, pp. 441-444.

[61] F. E. and C. W. Wright: Journal of Geology, vol. xvi, 1908, pp. 52-53.

[62] Otto Klotz: Geographical Journal, vol. xxx, 1907, pp. 419-421.

Fremont Morse: National Geographic Magazine, vol. xix, 1908, pp. 76-78.

During this same period from 1899 to 1907 Grand Pacific Glacier had retreated 8½ miles and the other ice-tongues of Glacier Bay smaller amounts.[63] Since Mr. Buschmann has testified that the increased flow of icebergs began with the September 10 earthquake, we may safely ascribe the initiation of the rapid retreat and loss of scenic beauty of the Muir Glacier to this shaking in connection with the Yakutat Bay earthquakes.

Canadian Coast Range.—At Atlin and Discovery City, British Columbia, in the Canadian Coast Range, about 215 to 230 miles east of Yakutat, the severe earthquake was felt in several mining camps on September 10,[64] as well as at the Hudson Bay post near Teslin Lake,[65] 275 miles east of Yakutat Bay.

On the southeast shore of Atlin Lake, Prof. J. C. Gwillim, of the Canadian Geological Survey, made the best of these earthquake observations.[66] The shock came at 12.45 p. m., local meridian time, corrected by a latitude observation on the sun at noon on that day. There was an undulating motion lasting about 30 seconds. Water was spilled out of small utensils being used at dinner. There was a heavy wind, so no earthquake water waves could have been detected on Atlin Lake.

In the Surprise Lake district, east of Atlin, British Columbia, there were earthquake shocks during the first half of September, 1899, the heaviest shock coming on September 10. Mr. John Bimms[67] observed what he interpreted as smoke from a supposed volcano, but what may have been dust from great avalanches in this part of the Canadian Coast Range. Certain glaciers were broken.

Lynn Canal.—At various points along this fiord and in the mountains near by, the great earthquake of September 10, together with those of the preceding Sunday, was felt by a great many people. Since Skagway, Haines Mission, Dyea, Pyramid Harbor, and Juneau are steamer landings, and as Skagway was connected by telegraph with Vancouver and Seattle, these observations were reported in a great many newspapers. The accounts[68] are of variable completeness and accuracy.

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[63] Compare U. S. Coast and Geodetic Survey Charts 3095 (1899) and 8306 (1910).

[64] Victoria Semi-Weekly Colonist, October 2, 1899.

[65] Reported by Mr. Archibald Ainslie.

[66] Summary Report for 1899, vol. xii, Annual Report Geological Survey of Canada, p. 62A.

[67] San Francisco Chronicle, October 5, 1899.

[68] Seattle Daily Times, September 20, 1899; same September 21, 1899; same, October 2, 1899; Seattle Weekly Times, September 27, 1899; same, October 4, 1899; Victoria Semi-Weekly Colonist, September 21, 1899; same, September 25, 1899; San Francisco Chronicle, September 22, 1899; Chicago Daily Tribune, September 23, 1899; Portland Weekly Oregonian, September 29, 1899; San Francisco Chronicle, October 5, 1899; Sitka Alaskan, October 7, 1899.

At Skagway, 160 miles east of Yakutat, Rev. B. F. Shelton reports six or seven shocks between 4 a. m. and 3 p. m. on September 10. The one at 11.40 alarmed the people in church, the vibrations increasing until every one felt the motions distinctly in their seats.

The shock at 12.40 (the great earthquake) was so violent that persons walking were thrown against the walls and it was necessary to cling to supports to keep from falling. There were earth-waves, causing a nausea like seasickness upon the ocean, especially among the women and children. People had a strange, pallid, half-frightened look, locally known as "the earthquake face." Lamps swayed violently, electric lights swung nearly to the ceiling, pictures rebounded from the wall, glass windows vibrated, crockery was knocked from shelves and some plaster fell, and gaps were opened in walls. C. L. Andrews, the deputy collector of customs, observed that the shock lasted long enough for him to take two children by the hand, run out of the office 25 feet down a hall, one story downstairs, and out into the street.

Skagway had a population of 3,117 in 1900, and presumably about the same number in 1899. It was the most severely shaken large town in the disturbed area, but had no loss of life or serious damage to property, largely because the dwellings were chiefly low frame structures, log cabins, and tents. An earthquake of this magnitude in New York or Chicago or San Francisco, with their brick and stone structures and tall office buildings, would have wrought tremendous damage to life and property.

In the Berners Bay district, on the east side of Lynn Canal and 180 miles southeast of Yakutat, Mr. H. W. Mellen, a mining engineer, observed the September 10 earthquake at the Jualin mine. There were two shocks, fifteen minutes apart, about 12.30 p. m. The first was a little the more severe, lasting long enough for a man to go into his office, pick up overturned lamps, come out, and walk 50 feet. The second lasted long enough for him to run 75 feet into a mine tunnel, call the miners, and run out again. The motion was severe enough to make a raincoat swing outward a foot from the wall on which it was hanging, to upset lamps, break dishes, slide a 24-inch book off a table, and make a man fall off a chair. Hard shaking came first, followed by undulations. There were distinct earth-waves, making people stagger in walking. Avalanches were heard. The direction of staggering in walking and of sliding of books and dishes indicated that the shock came from the northwest—that is, from the direction of Yakutat.

At Juneau, near the entrance of Lynn Canal and 220 miles southeast of Yakutat, the great shock of September 10 was also felt.[69] Judge H. H. Folsom, the United States commissioner, recorded this shock at 12.55 p. m. It lasted long enough for him to get out of a barber's chair, walk 20 feet to the sidewalk, and watch electric light poles sway. Buildings were shaken severely, especially the hotel, hospital, and churches, but no serious damage was done. Frightened people ran into the streets. Miners emerged hastily from the Treadwell gold mine at Douglas. Douglas and Juneau together had 2,689 inhabitants in 1900 and presumably about the same the year before, and only low wooden buildings. There were minor tremblings all day and another severe shock between 4 and 5 p. m.

Southeastern Alaska.—In Taku Inlet, southeast of Juneau, the earthquake was probably severe,[70] damaging the glaciers so that increased iceberg discharge began at once, as in the Glacier Bay and Icy Straits regions. Several of the fiords of the Inside Passage,[71] including Lynn Canal, Taku Inlet, Stephens Passage, and Gastineau Channel, were obstructed by ice. This resulted temporarily in difficulties in navigation, one vessel, the *Rosalie,* being damaged by collision with floating icebergs. The Taku Inlet glaciers seemed in 1905 to have recovered from their 1899 losses.[72] The net advance of Taku Glacier between 1890 and 1905, as proved by photographs,[73] may possibly be ascribed to earthquake avalanching in 1899, the snowfield being so augmented that although the tidal ice-front temporarily retreated, because of shaking and water disturbances, the glacier itself has eventually advanced, as those in Yakutat Bay have done.

At Sumdum, in southeastern Alaska, 275 miles southeast of Yakutat, Mr. R. V. Rowe, a carpenter, observed an earthquake on an unrecorded date in September, 1899, which caused a building he was erecting to rock for about ten seconds.

In McHenry Inlet, Etolin Island, Alexander Archipelago, 375 miles southeast of Yakutat, Mr. Fred Patching reports a sharp earthquake about 6.30 a. m. a Sunday morning in September, 1899, in connection with which great landslides occurred. This location is detached from the main shaken area and, because doubtful, has not been put on the map.

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[69] Seattle Daily Times, September 20, 1899; San Francisco Examiner, dispatch dated Juneau, September 14, 1899; New York Evening Post, September 21, 1899; New York Daily Tribune, September 22, 1899.

[70] Seattle Daily Times, September 22, 1899; San Francisco Examiner, dispatch dated Seattle, September 21, 1899.

[71] Victoria Semi-Weekly Colonist, September 25, 1899; same, October 12, 1899; Seattle Daily Times, September 21, 1899; same, September 22, 1899; Scientific American, vol. lccci, 1899, pp. 405-406; Current Literature, vol. xxvii, 1900, p. 123; xii Annual Report Geological Survey of Canada, 1899, p. 62A.

[72] H. F. Reid: Journal of Geology, vol. xiii, 1905, p. 317.

[73] H. F. Reid: Variations of Glaciers, Journal of Geology, vol. xiv, 1906, p. 408.

At Sitka, 260 miles southeast of Yakutat, the great earthquake of September 10 was sensible,[74] though rather slight. Bishop P. T. Rowe, who was lying down, was among those who felt it. Dr. C. C. Georgeson, who was walking out of doors, did not. Sitka was near the outer limit of the sensible shock in this direction, and from several towns near by, in southeastern Alaska, specific statements have been received that these earthquakes were not felt.

Lake Chelan, Washington.—On the east side of the Cascade Mountains, in the State of Washington (latitude about 47° 50′ north, longitude about 120° west), water waves were observed on Lake Chelan at the time when the tremors of the great earthquake of September 10 were traversing the region. Lake Chelan is nearly 1,200 miles from Yakutat Bay, Alaska (figure 1). The waves, observed on at least four points of the coast of this long, narrow lake, arose at about 2 p. m.[75] on an otherwise glassy lake, there being no wind. They rose 15 or 20 feet, driving a boat ashore and lasting nearly two hours.

The earthquake originated at Yakutat at 12.22 (about 1.40 on Lake Chelan). Transmission would occupy ten to twenty minutes or more. The seismograph at Victoria, British Columbia (figure 1), recorded this shock at 1.45[76] (equivalent to 1.59 at Chelan). The first waves were noted "at about 2 o'clock."

The phenomena might, of course, be due to (*a*) landslides or (*b*) a secondary earthquake. In the absence of evidence of these, there is no particular reason to doubt that the weak tremors were in some way naturally amplified in this long, deep, mountain valley, so that earthquake water waves were caused. In the Lisbon earthquake of 1755 water waves on lakes and ponds in England and on Loch Lomond, in Scotland, attended the shocks and at an even greater distance than from Lake Chelan to Yakutat Bay.

Résumé of the great earthquake of September 10.—This earthquake is known to have been felt at more than forty places (figure 4), varying in distance from 2 miles to 430 miles from the origin in Yakutat Bay. Water waves were probably caused nearly 1,200 miles away. The observations include earth movement, faulting, water waves, floods, avalanches, fissures, spouting from sand craterlets, difficulty in standing and walking, damage to buildings, a cemetery, etcetera, terror on the part of ani-

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[74] The Sitka Alaskan, September 16, 1899; Seattle Daily Times, September 28, 1899.

[75] San Francisco Chronicle, September 15, 1899; Salt Lake Semi-Weekly Tribune, September 19, 1899. Information obtained from C. E. Rusk, of Chelan, in 1909.

[76] Interview with Mr. Napier Denison, the Government observer, in the Victoria Semi-Weekly Colonist, September 21, 1899. Unfortunately this valuable seismograph was subsequently lost in the mails.

mals as well as man, and nausea. Shorelines were uplifted as much as 47⅓ feet and depressed as much as 5 feet in Yakutat Bay. New reefs were uplifted. Shattering of ice-fronts caused increased iceberg discharge for many tidal glaciers. Muir Glacier subsequently retreated 8 miles in 8 years. Avalanches caused a series of glacier floods, after an interval dependent on the length of the ice-tongue. Seven or more glaciers near Yakutat Bay had brief spasmodic advances with enormous crevassing within ten years, including part of Malaspina Glacier. The front of Hidden Glacier has advanced over two miles. There was no loss of life and scarcely any damage to property within the shaken area.

EARTHQUAKES OF SEPTEMBER 11 TO 29, 1899

Light after-shocks were felt at Yakutat all through the night of September 10 and others during the remainder of the month.

On the 11th a few slight shocks were noted at the Cape Whitshed Coast Survey camp near the Copper River delta. The earthquakes felt between the 12th and 16th were not precisely recorded, because the uproar of heavy storms then raging made it hard and uncertain to determine time and duration.

On September 15 severe shocks at 7.15 and 7.30 p. m. at Yakutat caused R. W. Beasley's lamps to swing and kettles to beat against each other, lasting long enough for him to run out of doors. At Skagway[77] the shocks came at 8.20 and 8.40 p. m., the first lasting 50 seconds. It caused electric lights to sway 18 inches and stopped pendulum clocks. Some houses moved; a pier and several houses were damaged; men staggered in walking. The shocks were reported by telegraph from Lake Bennett, on the Klondike trail.

On September 17 a shock was felt at Skagway, but not at Yakutat or Cape Whitshed.

On September 23 eight shocks were felt at Cape Whitshed; that at 1.22 a. m. lasted 2 minutes—long enough for a man to jump out of cot and light candles. It woke the Coast Survey party from sleep, causing a plumb bob to vibrate with half-second oscillations with an amplitude of 10 inches from northwest to southeast. It consisted of a short shock, followed after a few seconds by one of longer duration. The after-shocks came at 1h. 28m. 9s., lasting 2 seconds; at 1h. 3m. 9s. with equal duration; at 1h. 40m. 9s., consisting of two short shocks of a second each; at 1h. 41m. 51s., consisting of two shocks lasting a quarter of a

[77] Seattle Post-Intelligencer, September 23, 1899; Chicago Daily Tribune, September 23, 1899; Victoria Semi-Weekly Colonist, September 25, 1899; Seattle Weekly Times, October 4, 1899.

second each. Shocks were also felt on this date at Cordova and Valdez, on Prince William Sound, and at Sitka.

On September 26 four shocks were felt at Cape Whitshed, one of them at 2.40 a. m., during a rain-storm, waking sleeping men; one at 12h. 5m. 38s. p. m., lasting half a minute. There was a short shock at 2.46 p. m., and another during the night. One of these earthquakes seems also to have been felt at Eagle.

On September 29 the last earthquake of the series was sensible at Cape Whitshed during the night, the Coast Survey observers feeling none others before they left the Copper River delta on October 23. Light after-shocks were felt at Yakutat, however, all winter.[78] R. W. Beasley lists them as occurring December 14, 20, and 28, 1899; January 12 and 27, and February 16, 1900.

Seismograph Records

STUDY BY SEISMOLOGISTS

As has been pointed out by Dr. G. K. Gilbert,[79] this series of Yakutat Bay earthquakes is of importance because it belongs in the rather small group of adequately observed great shocks. "It ranks high in the scale of energy, the position of its origin has been determined with unusual precision, and its initial time is known with close approximation." More than this, it is an abnormal group of shocks[80] in its departure from the normal sequence of (1) prelude, (2) great shock, and (3) after-shocks. This group (figure 7) perhaps had no prelude (August 27?); there were at least four great shocks (September 3, 10, 10, 23); several other important ones (September 15, 17 (?), 26), and a long series of after-shocks.

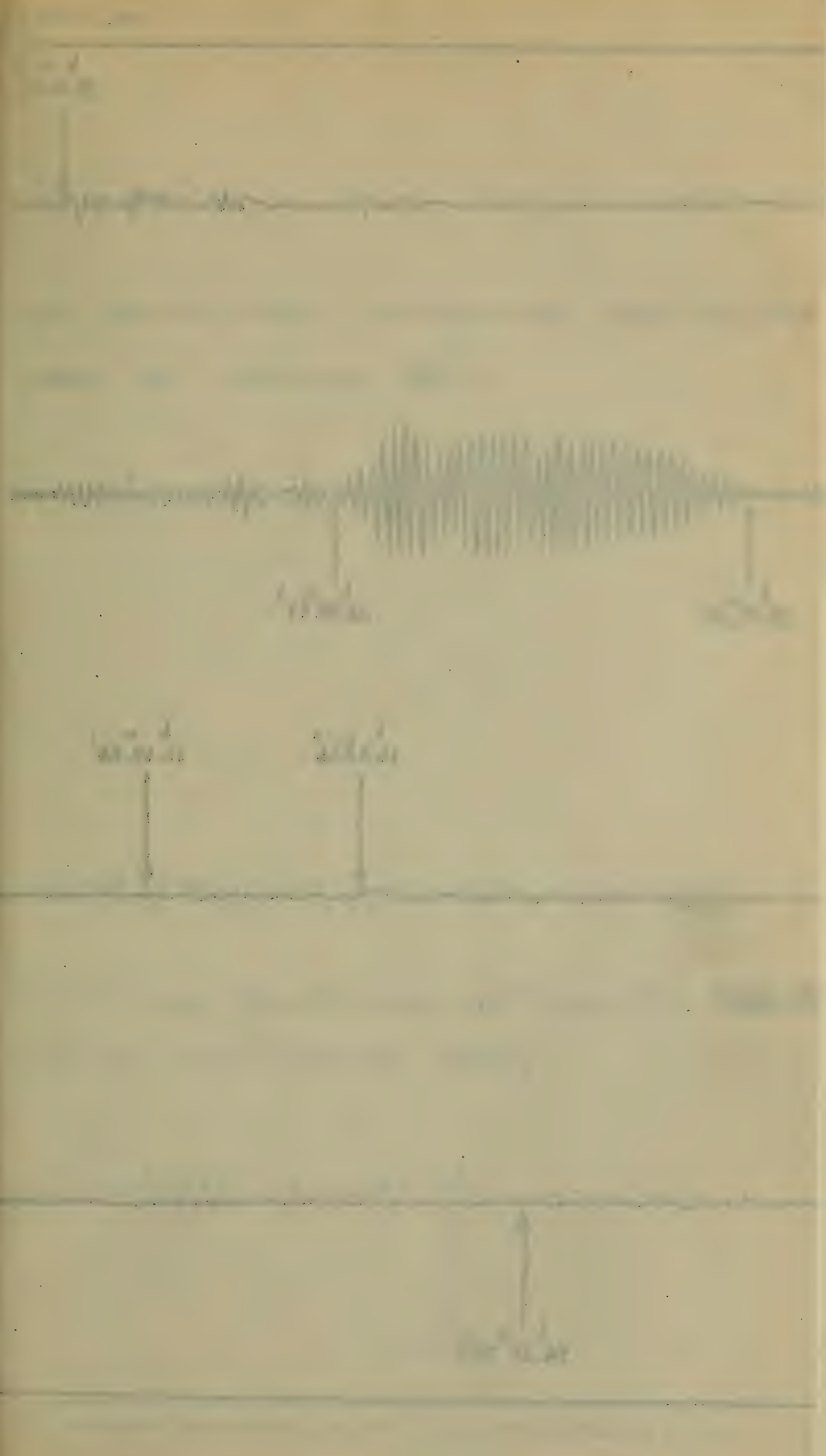
The seismograph records at Victoria, British Columbia (figure 1), the station nearest to Yakutat where precise instrumental observations were made, were first noticed, while the earthquakes were still in progress, in newspaper interviews with Mr. Napier Denison.[81] Afterwards these world-shaking earthquakes were studied by experienced seismolo-

[78] Rev. Albin Johnson: Report of Commissioner of Education for 1898-9, vol. 2, 1900, p. 1402.

[79] Preface to report on the Yakutat Bay (Alaska) earthquakes of September, 1899, by R. S. Tarr and Lawrence Martin, in Professional Paper of the U. S. Geological Survey (in preparation).

[80] G. K. Gilbert: Earthquake forecasts. Science, N. S., vol. xxix, 1909, pp. 126-127.

[81] Victoria Semi-Weekly Colonist, September 21, 1899; same, September 28, 1899; Chicago Times-Herald, September 25, 1899; New York Daily Tribune, September 25, 1899; San Francisco Examiner, September 25, 1899.



gists like Prof. John Milne,[82] Dr. F. Omori,[83] Dr. A. Cancani[84] and other Italian observers, Prof. E. Lagrange,[85] Dr. R. D. Oldham,[86] and others.

In 1900 the British Association for the Advancement of Science published 28 of the better seismograms of the Yakutat Bay earthquakes of September 3, 10, and 23, 1899.[87] The seismogram of the September 10 disturbance at Batavia, Java, is reproduced by Dr. J. P. van der Stok in an article, "Two earthquakes in Europe and at Batavia."[88] The Imperial Earthquake Investigation Committee of Japan published records of the September 3d and 10th shocks as recorded at the Tokio observatories of Hongo and Hitotsubashi.[89] The seismogram of the September 3d earthquake as recorded at Uccle, Belgium, was published in 1901.[90] The September 3d record of the nearest seismograph to Victoria, British

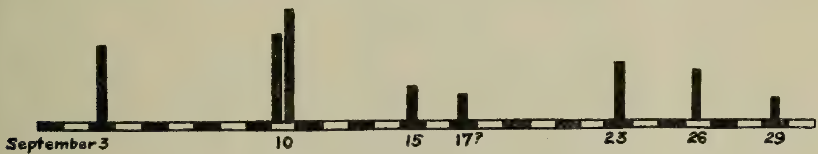


FIGURE 7.—*Earthquake Diagram*

Showing relative time intervals and approximate relative intensities of the eight most severe earthquakes at Yakutat Bay, Alaska, in September, 1899

Columbia, and, therefore, only 1,000 miles from Yakutat, and the Toronto records of the earthquakes of September 3 and 10 were reproduced by Dr. R. F. Stupart,[91] of the Meteorological Service of Canada.

Plate 29 shows the Catania records of the great earthquake of Septem-

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[82] J. Milne: Report of British Association for the Advancement of Science, 1900, pp. 64, 66, 68, 69, 70, 71, 72-73, 74, 77, 80, 82, 87, 95, 96-97, 98, 99, 100, 105, 108, and plates ii and iii; same, 1902, pp. 62, 64.

[83] F. Omori: Publications of Earthquake Investigation Committee in foreign languages, no. 5, Tokio, 1901, pp. 21, 26, 37, 38, 39, 40, 47, 48, 49, 50, 59, 62, 63; same, no. 6, 1901, 47-48, 49-50, 50-51, 51-52; same, no. 13, 1903, 87, 88, 96-99, 112, 114, 117, 121, 122, 123; same, no. 21, 1905, 45-49, 60, 71, 76, 77, 79, 80, 81, 85, 88, 89.

[84] A. Cancani: Noticie sui terremoti osservati in Italia durante l'anno 1899. Appendice al Bollettino della Societa Sismologica Italiana, vol. 6, Modena, 1900-1901, pp. 178-190, 194-198, 199-208, 223-227.

[85] E. Lagrange: Les Movements Sismiques en Belgique en 1899. Bull. de la Soc. Belge d'Astronomie, 5me. année, 1901, no. 2, p. 4.

[86] R. D. Oldham: Quarterly Journal of the Geological Society, vol. lxii, 1906, pp. 459, 461, 471.

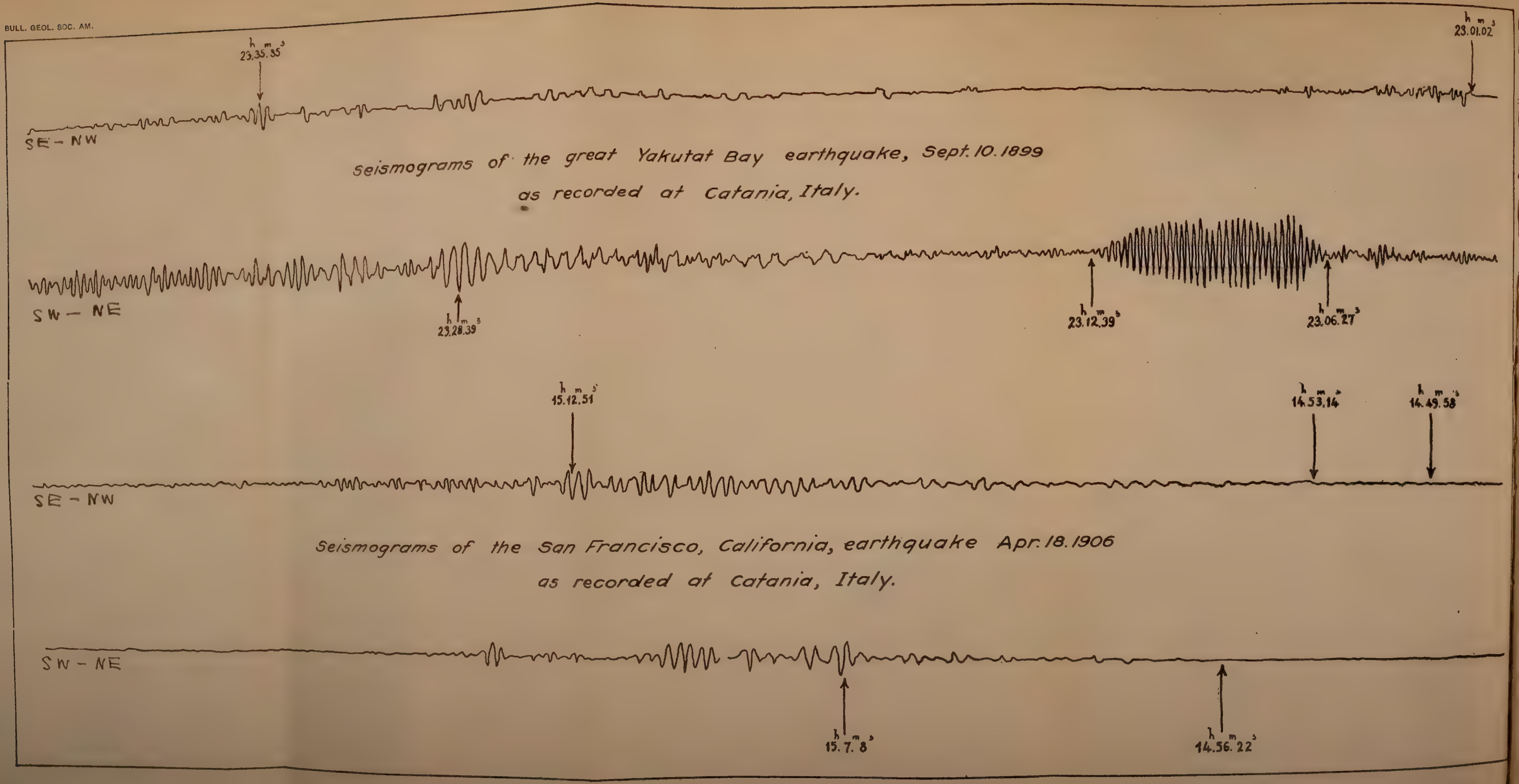
[87] Fifth Report, Committee on Seismological Investigation, British Association for the Advancement of Science, 1900, pp. 95-97, 100.

[88] Koninklijke Akademie van Wetenschappen te Amsterdam. Proceedings of the Section of Sciences, vol. ii, 1900, plate opposite page 246.

[89] Publications of Earthquake Investigation Committee in foreign languages, no. 5, 1901, plates vii and viii; same, no. 21, 1905, plate xxxvi.

[90] Bull. Société Belge d'Astronomie, 5me. année, 1901, no. 2, plate xii.

[91] Proceedings and Transactions of the Royal Society of Canada, second series, vol. ix, section iii, 1903, plate opposite page 71.



COMPARISON OF ONE OF THE YAKUTAT BAY EARTHQUAKES OF 1899 WITH THE CALIFORNIA EARTHQUAKE OF 1906

ber 10, 1899, at Yakutat Bay. In order to compare the duration and magnitude of this Alaskan earthquake with that of San Francisco, California, the record of Catania is also shown. The distances being nearly equal and the paths equivalent, a direct comparison may be made. These show the records from instruments in two planes at right angles and are from heavily weighted vertical pendula with mechanical registration. Records of the Omori horizontal pendula at Tokio as affected by the earthquakes of September 3 and 10 are shown in plate 30.

LOCATION OF ORIGIN FROM SEISMOGRAMS

As early as September 27, 1899, Prof. John Milne located the origin of the earthquakes of September 3 and 10 in Alaska.[92] He later made the more specific location in the Pacific Ocean west of Alaska, near latitude 50 degrees north and longitude 150 degrees west, noting on the map[93] that the origin might possibly be moved 10 degrees to the east. Dr. F. Omori located the origin of these earthquakes, making the latitude 60 degrees north, the longitude 140 degrees west.[94] Dr. R. D. Oldham[95] states that these shocks originated in latitude about 59° 5′ north and longitude 140° 0′ west. Field studies in 1905 and 1909 lead to the location of the earthquake origin in Yakutat Bay fiord. This is near latitude 59° 58′ 20″ north and longitude 139° 33′ 0″ west (see figure 5). This, of course, assumes a single origin and places it along an old fault-line associated with the 47⅓-foot uplift, the greatest observed change of level of the land in 1899. It seems correct for the great earthquake of September 10. The origins of the other earthquakes may have been slightly different and were perhaps not simple and single, but complex.

INTERVALS AND TIMES OF MAXIMA

From some of the best of the distant seismograph records Dr. R. D. Oldham has computed the intervals and compared them with the observed times of maxima of the three largest earthquakes.[96]

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[92] Nature, vol. lx, 1899, p. 545.

[93] Report of British Association for the Advancement of Science, 1900, pl. iii, opposite p. 77.

[94] Publications of Earthquake Investigation Committee in foreign languages, no. 5, pp. 61-65; no. 6, 1901, p. 51; no. 13, 1903, pp. 86-88.

[95] Quarterly Journal of the Geological Society, vol. lxii, 1906, p. 459.

[96] Unpublished manuscript. For a slightly different result with some of the same data, see Report of the British Association for the Advancement of Science, 1900, p. 77.

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Great Alasca Earthquakes, Observed at Hongo, Tokyo.

EW Component. Multiplication=10

TOKIO SEISMOGRAMS OF ALASKAN EARTHQUAKES

Place of observation.	Distance from epicentra in degrees.	Calculated interval in minutes at 3 km. per second.	Recorded time of maxima in minutes after origin.		
			September 3.	September 10.	September 10.
Victoria	14.2	8.8	12.0	....	....
Toronto	39.0	24.2	23.5	23.8	23.6
Tokio	55.5	34.4	28.5	....	29.5
Tokio	....	....	30.0	....	....
Kew	64.4	39.9	42 5	48.6	41.1
Shide	65.1	40.4	41.0	46.3	44.0
			41.2	....	....
Trieste	73.0	45.3	68.4	54.0	48.5
Trieste	....	45.3	71.0	48.6	46.4
Trieste	....	45.3	51.0	46.3	46.9
Padua	73.1	45.4	54.5	50 5	47.5
		45.4	60.5	55.5	46.5
		45.4	54.5	50.0	45.5
		45.4	60.5	....	47.5
Quarto	74.3	46.1	49.5	47.5	46.2
		46.1	48.5	....	60.5
		46.1	48.5	....	......
Rome	76.5	47.4	....	53.8	42.5
Rocca di Papa	....	....	....	51.5	44.5
			47.5	54.1	46.3
			65.1	54.1	45.3
			52.5	48.7	....
			51.3	....	....
			52.7	....	....
San Fernando	76.8	47.6	56.5	48.2	45.4
Ischia	77.7	48.2	52.5	....	55.5
Ischia	....	....	66.0	....	....
Catania	81.3	50.7	53.1	52.8	49 1
Catania	....	....	54.1	58.8	56.1
Bombay	95.5	60 6	58.0	57.3	58.6
Batavia	107.5	66.6	....	71.7	76.8
Cordoba	109.3	67.8	....	69.3	83.3
Mauritius	138.0	85.6	91.0	....	87.7
Capetown	149.6	92.8	91.0	90.5	84.7
Capetown	210.4	....	111.5	107.5	102.0
San Fernando	283.2	....	169.0	....	....
Rocca di Papa	283.5	....	169.5	....	....
Trieste	....	....	....	131.5	....
Toronto	321.0	....	214.5	....	194.5
Victoria	345.8	....	219.5	....	....

SEISMOGRAPH RECORD COMPARED WITH LOCAL ACCOUNTS

The most reliable of the local accounts show that the principal earthquakes felt in Alaska came on the following dates and at hours listed below. The origin in most cases was near Yakutat, but the nearest accurate time record was usually at Cape Whitshed.

Date.	Yakutat Village,[a] latitude 59° 33′ north, longitude 139° 45′ west.	Cape Whitshed,[b] latitude 60° 27′ 34″ north, longitude 145° 54′ 35″ west.
	P. M.	P. M.
September 3	(*)	2h. 40m.
After-shocks		3h. 22m. 30s. (*) 6h. 45m. 7h. 10m. 7h. 44m.
	A. M.	A. M.
September 10[c]	7h. 40m.	7h. 43m.
After-shocks		8h. 1m. 10h. 38m. 34s. 10h. 53m. 45s. 10h. 59m. 55s. 11h. 5m. 5s.
	P. M.	A. M.
September 10[d]	12h. 15m.	11h. 58m. 33s.
		P. M.
After-shocks		12h. 7m. 8s. 5h. 36m. 8s. 5h. 44m. 2s. 5h. 51m. 41s.
	P. M.	
September 15[e]	7h. 15m. 7h. 30m.	
September 17[f]		
		A. M.
September 23		1h. 22m.
After-shocks		1h. 28m. 9s. 1h. 33m. 9s. 1h. 40m. 9s. 1h. 41m. 51s.
		A. M.
September 26		2h. 49m.
		P. M.
		12h. 5m. 38s. 2h. 46m.
September 29		During night.

[a] Observed at Yakutat Village by R. W. Beasley. Irregularly regulated "sun time" of local meridian.

[b] Observed in Coast Survey camp by H. P. Ritter, with good and well rated chronometer, using solar time of local meridian.

(*) No time record.

[c] The early shock.

[d] The great earthquake.

[e] Not recorded at Cape Whitshed. Shocks were felt between September 12 and 16, but not precisely recorded because of general uproar of storm then raging. This September 15th shock was felt with great intensity at Yakutat, as well as at Skagway.

[f] If observed at Yakutat or Cape Whitshed the shock was not recorded. Indefinite statement of observation at Skagway and Juneau.

No time record is available for the possible initial shock on August 27, 1899, but there seems to have been no great shock recorded by seismographs that day. All the seismograph records, so far as known to the writer, show world-shaking earthquakes on September 3, twice on September 10 and September 23 at most of the observatories where instruments were then installed (figure 8).

There seems to have been no seismograph record of the September 15th shock, although reported as severe at Yakutat, Skagway, etcetera.

The September 17th shock, though widely recorded by seismographs, was not felt at Yakutat or Cape Whitshed. Its observation at Skagway and Juneau is indefinite. Professor Milne has computed, however, that this shock was in Alaska.[97] Its origin was probably not in Yakutat Bay.

The shock of September 23 was recorded throughout the world, the record having an amplitude of 17 millimeters at Victoria and then going clear off the paper.

The shock of September 26 was recorded throughout the world, but was less violent than that of the 23d. Its amplitude was 7.4 millimeters at Victoria and 4.1 millimeters at Toronto.

The shock of September 29, the final one of the series, happens to coincide in date with the Ceram earthquake in the East Indies. The Victoria seismogram, with an amplitude of 2.5 millimeters, might possibly belong to the Alaskan series, but the exact time of the shock felt in the night at Cape Whitshed is not available for determining this conclusively.

TABLES OF SEISMOGRAPHIC DATA

The following three tables include some of the available data showing the orderly and progressive time, duration, and intensity as the tremors

[97] Nature, vol. lx, 1899, p. 545.

of the three largest earthquakes originating at Yakutat moved outward through the earth's crust and interior. The figures selected are taken chiefly from circulars 1 and 2 of the Seismological Committee of the British Association for the Advancement of Science. All records are from Milne horizontal pendulums of the same general type, recording is uniformly done, the magnification of amplitude is the same, and observations may, therefore, be roughly compared. All observations are reduced to Greenwich mean time.

The places of observation are shown in figure 8. The observed times at the Alaskan localities are placed for convenience in the first column, although not seismographic and not exactly equivalent to the commencement of the preliminary tremors. It is recognized that the recorded maxima on seismographs with little damping are largely instrumental and do not correspond to the greatest movement of the earth. It should be stated that these are based on old calculations, and that trained seismologists might now determine the times and occurrences of the various shocks with greater accuracy, in view of the most recent seismological studies. The main facts, however, are briefly assembled here for convenience of reference.

Shock of September 3–4, 1899

Place of observation.	Commencement of preliminary tremors.	Maximum.	Amplitude in millimeters or seconds of arc.	Total duration.
	h. m. s.	h. m. s.		h. m. s.
Yakutat (Disenchantment) Bay, Alaska.	0 21 40*	....	....	....
Cape Whitshed, Alaska.	0 23 38	....	....	....
Victoria, British Columbia.	0 26 13	0 35 9	Off paper..........	....
Toronto, Canada.....	0 30 14	0 48 19	24 millimeters.....	7 54 19
Tokio, Japan........	0 30 65[a]	....	1.35 millimeters[h] ..	1 17
Kew, England	0 33.6	1 3.0[b]	7.49 inches........	2 49.2
Shide, England......	0 35.0[c]	1 1.5	15.0 millimeters[f] ..	....
San Fernando. Spain.	0 33.6	1 7.1	8.17 inches........	3 19.9
Bombay (Colaba), India.	0 45 25	1 18 34	4.66 inches........	....
Cordoba, Argentina..	0 40.8[e]	1 52.4	6.5 millimeters	3 14.6
Mauritius, Indian Ocean.	....	1 51.5[g]	5.70 inches........	....
Capetown, South Africa.	0 46.2	1 51.5[d]	2.5 inches.........	....

* Computed by Dr. R. D. Oldham from seismograph records as 0h. 20m. 30s.

a 0h. 31m. 52s.

b First maximum, 1h. 3.0m.
Second maximum, 1h. 7.3m.

c Or 23h. 49.1m.

d Or 2h. 0.9m., or 2h. 12.0m. times. Recorded roughly on account of failure of occultation watch.

e Given as 20h. 40.8, September 4, probably error for 0h. 40.8m.

f Boom caught at maximum by eclipse plate of watch.

g Beginning and end lost in air tremors.

h Amplitude of principal portion given elsewhere as 15.2 millimeters.

Early Shock of September 10, 1899

Place of observations.	Commencement of preliminary tremors.	Maximum.	Amplitude in millimeters or seconds of arc.	Total duration.
	h. m. s.	h. m. s.		h. m.
Yakutat (Disenchantment) Bay, Alaska.	17 01. 30 [a]	....	....	....
Cape Whitshed, Alaska.....	([a])	....	....	....
Victoria, British Columbia..	Lost in mails.	....	Vibrations across paper.	....
Toronto, Canada...........	17 11 56	17 25 19	....	....
Kew, England.............	17 15.3	17 50.1 [b]	2.18 inches exceeded.	1 39
Shide, England	....	17 48.0	....	2 12.2
San Fernando, Spain.......	17 9.9	17 47.1	2.58 inches..	....
Bombay (Colaba), India....	....	17 58 47	0.78 inch....	....
Madras, India..............	17 28.3	18 { 3.2 [c] / 12.5 }	{ 1.0 / 0.7 }	....
Batavia, Java...............	17 30.2	18 8.2	2.0 inches...	1 16
Cordoba, Argentina........	17 32 8	18 10.8	2.0 mm.	2 12
Cape Town, South Africa...	17 36.2	18 { 32.1 / 34.6 }	} 0.5inch	2 0

a The time of origin given above for Disenchantment Bay was computed by Dr. R. D. Oldham from seismograph records.

b First maximum, 17h. 50.1m.
Second maximum, 17h. 53.5m.

c Clock stopped at 18h. 36m.

The great Earthquake of September 10, 1899

Place of observation.	Commencement of preliminary tremors.	Maximum.	Amplitude in millimeters or seconds of arc.	Total duration.
	h. m. s.	h. m. s.		h. m. s.
Yakutat (Disenchantment) Bay.	21 40 13[a]	....	....	....
Cape Whitshed, Alaska.	21 42 11	....	....	....
Atlin, British Columbia.	21 39 20	....	....	....
Eagle, Alaska.........	21 40	....	....	....
Victoria, British Columbia.	"Splendid seismogram lost in the mails."		"Over an inch."	
Toronto, Canada......	20 42 14	22 3 6	Vibrations across paper.	5 36 55
Kew, England.........	21 1.6	22 20.21[b]	10.8 inches.......	3 0
Shide, England.......	21 23.0	22 23.5	....	....
San Fernando, Spain..	21 3.9	22 24.9	14.62 inches......	4 11.8
Bombay (Colaba), India.	....	22 38 9	1.78 inches.......	....
Batavia, Java.	22 0.0	22 56.3	9.3 inches	2 11
Cordoba, Argentina...	21 56.8	23 2.8	5 millimeters	....
Mauritius, Indian Ocean.[c]	....	23 { 7.2 15.0	1.47 inches....... 1.44 inches.......	....
Capetown, South Africa.	22 1 4	23 { 0.4 4 2 9.1 13.3 21.5	2.4 inches	3 30

a The apparent anomaly of the shock being felt at Toronto, etcetera, before it was recorded at the origin is probably due to the fact that the extremely delicate first movements which separate into the preliminary tremors were well started on the way before the more severe motion, perceptible to the senses of persons nearer the origin, was recorded. Doctor Oldham computes this same origin as 21h. 39m. 30s.

b First maximum, 22h. 20.21m.
Second maximum, 22h. 25.6m.

c Air tremors marked beginning and end.

MAGNETOGRAPH RECORDS

Instruments for the measurement of terrestrial magnetism also recorded the Yakutat Bay earthquakes. The optical registration and the accurate time observation make these valuable as earthquake records. So far as reported, the magnetographs recorded these shocks at Toronto, Canada;[98] Utrecht, Holland, and Wilhelmshaven, Germany, but not at

[98] Fifth Report of the Seismological Committee of the British Association for the Advancement of Science, 1900, p. 83.

Greenwich or Falmouth, England; Parc St. Maur, Paris, and Perpignan, France; Copenhagen, Denmark, or Manila, Philippine Islands.

PLACES OF INSTRUMENTAL RECORDS

Beside the places listed in the tables above, the Yakutat Bay earthquakes were recorded at many other observatories. The following list of places of observations has been compiled to show the world-shaking

FIGURE 8.—*Map showing Seismograph Stations*

Yakutat, Alaska, and seismograph stations throughout the world at which the earthquakes of September, 1899, were recorded

character of the principal shocks. It is also partly bibliographic. The location of these places is shown in figure 8. Many of the instrumental records are from circulars 1 and 2 of the Seismological Committee of the British Association for the Advancement of Science (Prof. J. W. Judd, chairman; Mr. John Milne, secretary). Some of the others refer to unpublished materials furnished for the U. S. Geological Survey Professional Paper dealing with these earthquakes, by R. S. Tarr and the writer.

North America

Place.	Type of seismograph.	Described by	Published in
Victoria, British Columbia.	Milne	Seismological Committee.	Circular 2, B. A. A. S., 1900, pp. 38–39.
Toronto, Ontario	Milne	Seismological Committee.	Circular 2, B. A. A. S., 1900, pp. 36–37.
Toronto (Agincourt), Ontario.	(Magnetograph).	R. F. Stupart.	Personal communication.
		J. Milne	B. A. A. S., 5th Report Seismological Committee, 1900, p. 83.
City of Mexico, Mexico.	Milne	.....	.....

South America

Cordoba, Argentina	Milne	Seismological Committee.	Circular 2, B. A. A. S., 1900, pp. 50–51.

Europe

Shide, Isle of Wight.	Milne	John Milne	Circular 1, B. A. A. S., 1900, p. 3.
Kew, England	Milne	Seismological Committee.	Circular 1, B. A. A. S., 1900, pp. 6–7, 9.
Uccle, Belgium	Rebeur-Ehlert	E. Lagrange	Bull. Soc. Belge d'Astron. 5me Année, 1901, No. 2, p. 4.
Utrecht (de Bilt), Holland.	(Magnetograph)	G. van Dyk	Personal communication.
Hamburg, Germany.	Rebeur-Ehlert	R. Schült	Personal communication.
Wilhelmshaven, Germany.	(Magnetograph).	H. Capelle	Personal communication.
Göttingen, Germany.	.....	L. Geiger	Personal communication.
Strassburg, Germany.	Rebeur-Ehlert	A. Rudolph	Personal communication.
		J. P. van der Stok.	Konink. Akad. Wetens. te Amsterdam, vol. ii, 1900, pp. 244–246.
Grenoble, France	.....	Paul Reboul	Personal communication.
San Fernando, Spain.	Milne	Seismological Committee.	Circular 1, B. A. A. S., 1900, p. 64.
Rome (Rocca di Papa), Italy.	Agamennone and Vicentini vertical pendula and two horizontal pendula.	G. Agamennone.	Boll. Soc. Sism. Ital., vol. vi, 1900–1901, pp. 178–182, 194–196, 199–202, 224.
Catania, Italy	.....	A. Riccó	Boll. Soc. Sism Ital., vol. vi, 1900–1901, pp. 186–187, 197, 204–205, 225.
Naples (Casamicciola), Italy.	Six instruments.	G. Grablovitz.	Boll. Soc. Sism Ital., vol. vi, 1900–1901, pp. 183–186, 202–204, 224–225.
Naples (Portici), Italy.	.....	.....	.....

Europe—Continued

Place.	Type of seismograph.	Described by	Published in
Rome, Italy	....	S. S. del Coll. Rom.	Boll. Soc. Sism Ital., vol. vi, 1900–1901, pp. 182–183, 194, 199, 223.
Florence (Quarto Castello), Italy.	Vicentini and others.	A. Bastogi, D. R. Stiattesi.	Boll. Soc. Sism. Ital., vol. vi, 1900–1901, pp. 187–189, 197–198, 205–207, 225–226.
Padua, Italy	....	....	....
Pavia, Italy	....	E. Oddone	Boll. Soc. Sism. Ital., vol. vi, 1900–1901, pp. 189, 198, 207, 226–227.
Siena, Italy	Vicentini	....	Boll. Soc. Sism. Ital., vol. vi, 1900–1901, p. 205.
Turin, Italy	....	R. Osserv. Astron.	Boll. Soc. Sism. Ital., vol. vi, 1900–1901, pp. 189-190, 207–208.
Trieste, Austria	Rebeur-Ehlert	E. Mazelle	Mitt. d. Erdb. Komm. d. kais. Akad. Wiss. in Wien, Bd. cix, 1900, pp. 28–31, 34-35.
Kremsmünster, Austria.	....	P. F. Schwab.	Mitt. d. Erdb. Komm. d. kais. Akad. Wiss. in Wien, xv, 1900, pp. 42–45.
Laibach, Austria	Vicentini	A. Belar	Boll. Soc. Sism. Ital., vol. vi, 1900–1901, pp. 190, 208, 227.
Nicolajew, Russia	....	J. Kortazzi	Beiträge Z. Geophysik, vol. iv, 1900, pp. 404–405.
Jurjew (Dorpat), Russia.	Zollner-Repsold, Rebeur-Paschwitz.	G. Lewitzky.	Personal communication.

Asia

Tokio (Hongo), Japan.	Omori	F. Omori	Pubs. E. I. C. (foreign languages), No. 6, 1901, pp. 48–51.
Tokio (Hitotsubashi), Japan.	Omori	F. Omori	Pubs. E. I. C. (foreign languages), No. 13, 1903, pp. 96–99; No. 21, 1905, pp. 46–49.
Tokio, Japan	Milne	Seismological Committee.	Circular 1, B. A. A. S., 1900, pp. 24–25.
Batavia, Java	Milne	Seismological Committee.	Circular 1, B. A. A. S., 1900, p. 20.
		R. D. M. Verbeek.	Konink. Magn. en Met. Obs., Batavia, vol. xxii, 1899, part i.
Bombay (Colaba), India.	Milne	Seismological Committee.	Circular 1, B. A. A. S., 1900, p. 13.
Madras, India	Milne	Seismological Committee.	Circular 1, B. A. A. S., 1900, p. 12.

Africa

Place.	Type of seismograph.	Described by	Published in
Mauritius, Indian Ocean.	Milne...........	Seismological Committee.	Circular 1, B. A. A. S., 1900, p. 17.
Cape Town, South Africa.	Milne...........	Seismological Committee.	Circular 1, B. A. A. S., 1900, p. 22.

Times of Yakutat Bay Earthquakes

DETERMINED FROM SEISMOGRAMS

Dr. D. W. Oldham has computed the time of origin of the three largest Yakutat Bay earthquakes[99] from the distant seismograph records. These times he determined, with an error of not more than one minute of time, by the use of curves first produced in his paper, "The propagation of earthquake motion to great distances."[100]

In a personal communication, which he has kindly allowed me to use, he states that in this computation he used

"the records of the Italian seismographs and adopted this course for two reasons; that, as shown in the paper referred to, the heavily weighted pendula with mechanical record give much more concordant results for the first two phases than light pendula with a slow-moving photographic record, and, 2d, because the curves having been deduced from the records of instruments of the type used in Italy, it is logical to use the data obtained from instruments of this type in applying them to obtain the time of origin of an earthquake.

"In the case of the Alaskan earthquakes the Italian observatories are distant from 73 degrees, in the case of Padua, to 81 degrees in the case of Catania. The mean time interval, as deduced from the curves, is consequently about 13.5 minutes for the first and 23.5 minutes for the second phase. I have consequently extracted from the published accounts the times of commencement, and, where recorded, of the first marked increase of movement, representing the second phase; these are tabulated below and the resulting time of origin deduced. The times so obtained are doubtless subject to a slight error, but this probably does not exceed one minute of time—an error which becomes insignificant when dealing with the comparatively slow traveling waves of the third phase. (The times tabulated here have been obtained, in the case of Padua, directly from the diagrams obtained there, which Professor Vicentini very kindly allowed me to examine; in the case of the observatory at Quarto (Florence), from the publications of that observatory, and in the case of the other Italian observatories, from the details published in part ii of the Bolletino della Societa Sismologica Italiana.)

[99] Quarterly Journal of the Geological Society, vol. lxii, 1906, p. 459.
[100] Philosophical Transactions of the Royal Society of London, series A, vol. 194, 1900, pp. 35-74.

Earthquake of September 4, 1899—Shide No. 333

Distance.	Place.	First phase.		Second phase.	
Degrees.		*h.*	*m.*	*h.*	*m.*
73.1	Padua	0	34.3	0	44
		0	34.3	0	45
		0	34.3	....	
74.3	Quarto	0	33.8	....	
		0	33.8	....	
		0	34.5	....	
		0	33.8	....	
		0	33.8	....	
76.5	Rome	0	34.6	0	46.5
		0	34 7	....	
76.5	Rocca	0	33.3	0	43.6
		0	35.5	....	
		0	34.5	0	45.0
		0	34.6	....	
		0	34.25	....	
77.7	Ischia	0	34.5	0	44.5
		0	34.5	0	44.5
		0	34.6	0	44.5
		0	34.5	0	44.3
		0	34.5	0	44.3
		0	34.7	0	44.3
		0	34.6	0	45.5
		0	34.6	0	44.4
81.3	Catania	0	34.7	0	45.7

"The mean time for the first phase may be taken as about 0h. 34m., and for the second phase as about 0h. 44m., giving the time of origin as 0h. 20.5m., Greenwich mean time.

Earthquake of September 10, 1899—Shide No. 337

Distance.	Place.	First phase.		Second phase.	
Degrees.		*h.*	*m.*	*h.*	*m.*
73.1	Padua	17	15.1	17	24.7
		17	15.2	....	
		17	15.1	....	
74.3	Quarto	17	15.0	17	24.5
		17	14.7	....	
		17	14.7	....	
76.5	Rome	17	15.6	17	25.8
76.5	Rocca	17	15.2	17	25.0
				17	25.1
77.7	Ischia	17	15.7	17	25.6
81.3	Catania	17	15.3	17	25.0

"The mean time for the first phase is 17h. 15m. and for the second phase 17h. 25m., giving 17h. 1.5m., Greenwich mean time, as the time of origin.

Earthquake of September 10, 1899—Shide No. 338

Distance.	Place.	First phase.		Second phase.	
Degrees.		*h*	*m.*	*h.*	*m.*
73.1	Padua	21	53.1	22	2.7
			53.1	22	2.3
			53.0	....	....
74.3	Quarto	....	....	22	9.8(?)
				22	9.8(?)
				22	2.7
76.5	Rome	21	50.5	....	....
76.5	Rocca	....	....	22	3.2
		21	53.4	22	3.6
		21	53.4	22	3.4
77.7	Ischia	21	53.5	22	3.5
81.3	Catania	21	52.9	22	1.0

"The resulting mean time for the first phase is about 21h. 53m.. and for the second phase 22h. 3m., which give a corrected time of 21h. 39.5m., Greenwich mean time, as the time of origin."

ALASKAN TIME RECORDS

The time records from Alaska which it is safe to use are from only three localities (figure 4). This is because (*a*) there were only a few persons in this wilderness area in September, 1899; (*b*) only a few of these persons observed the times of the earthquake shocks accurately, and (*c*) the timepieces of the few reliable observers were imperfect, the exact position was not known, or the timepiece was not afterwards corrected to given mean time of the local meridian.

The first of the three most reliable time records comes from Mr. H. P. Ritter, assistant, U. S. Coast and Geodetic Survey, who was at Cape Whitshed, Alaska, 220 miles west of Yakutat. His readings were taken with a good and well rated chronometer, giving mean local time of a point whose exact latitude and longitude had been determined. The second records were made by Judge W. G. Myers, local observer, U. S. Weather Bureau, at Eagle, Alaska, 340 miles north of Yakutat. His record is based upon local solar time. The third observations are by Prof. J. C. Gwillim, of the Geological Survey of Canada, who was near Atlin Lake, British Columbia, about 220 miles east of Yakutat. He had determined his position and set his watch to solar time only 45 minutes before one of the earthquakes.

Other records, not quite so accurate, are by R. W. Beasley, at Yakutat; Lieut. W. C. Babcock, of the U. S. Army, in the Chugach Mountains; Messrs. Brooks and Peters, of the U. S. Geological Survey, on the Tanana

River; Messrs. Schrader, Gerdine, and Witherspoon, of the U. S. Geological Survey, on the Koyukuk River, and others. These last three parties were engaged in topographic work, and their records might possibly be adjusted. The time observations at Skagway and other points on the telegraph line should also be fairly correct.

The times of origin in inner Yakutat Bay (Disenchantment Bay) have been determined as follows: The first earthquake on September 3 was recorded at Cape Whitshed,[101] the Coast Survey camp near the Copper River delta, at 2.40 p. m. Allowing a correction of 25 minutes and 26 3-10 seconds of time for 6 degrees 21 minutes and 35 seconds of longitude and a correction of 1 minute and 58 seconds of time for transmission about 220 miles, at the arbitrary rate of 3 kilometers, or a little over two miles per second,[102] we determine the time of origin of the shock of Disenchantment Bay as about 3.03½ p. m. September 3 (3h. 3m. 28⅓s., local time at Yukatat, or 0h. 21m. 40⅓s. a. m., September 4, when reduced to Greenwich mean time).

The first shock recorded on September 10 at Camp Whitshed came at 7.43 a. m. When this is corrected for longitude and transmission as above, it is found that it would have been felt at Disenchantment Bay at 8.06½ a. m. (8h. 6m. 28⅓s., local time at Yakutat, or 17h. 24m. 40⅓s., September 10, in Greenwich meridian time). This is about 23 minutes later than the shock shown by the seismograph records should have originated, and forces us to conclude that either (*a*) the first shaking at the Coast Survey camp was mild and not recorded, because coming just at or near the time of rising, or (*b*) that this shock was not central in Disenchantment Bay, but originated somewhere else in the mountains near by. The intensity of the first shock felt in the prospector's camp in Disenchantment Bay is against this hypothesis, and the time record by R. W. Beasley at Yakutat Village (7.40 a. m.) indicates the former to have been the case. Mr. Beasley's sun time, though close, is not precise enough, and we have adopted Doctor Oldham's seismograph time record for the origin of this shock, as is shown on a subsequent page.

A similar correction for longitude and transmission fixes the time of origin of the heaviest shock on September 10, which was recorded at the Coast Survey camp at 11h. 58m. 33s. as about 12.22 p. m. (12h. 22m. 1s.) local time in Disenchantment Bay, or 21h. 40m. 13s. when reduced to Greenwich mean time.

The September 15th earthquake, observed at Yakutat at 7.15 a. m.

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[101] Camp Whitshed, longitude 145° 54′ 35″ west, latitude 60° 27′ 34″ north; Disenchantment Bay, longitude 139° 33′ 0″ west, latitude 59° 58′ 20″ north.

[102] This may have been as great as 7 or 8 kilometers per second.

(not recorded at Cape Whitshed), originated at 7h. 15m., local time, at Yakutat, or 16h. 33m. 12s., Greenwich mean time.

The September 23d earthquake, observed at Cape Whitshed at 1h. 22m. a. m., originated at Yakutat at 1h. 45m. 28s., or 11h. 3m. 40s., Greenwich mean time.

The September 26th earthquake, observed at Cape Whitshed at 2h. 49m. a. m., originated at Yakutat at 3h. 12m. 30s., or 12h. 40m. 42s., Greenwich mean time.

THE CORRECTED TIMES OF ORIGIN

Date.	Time at Yakutat Bay.				Same in Greenwich mean time.			
	h.	*m.*	*s.*		*h.*	*m.*	*s.*	
September 3....	3	3	28	p. m.......	0	21	40	(September 4.)
September 10....	7	43	18	a. m.......	17	1	30	
September 10....	12	22	1	p. m.......	21	40	13	
September 15....	7	15		a. m.......	16	33	12	
September 17....								
September 23 ...	1	45	28	a. m.......	11	3	40	
September 26 ...	3	12	30	a. m.......	12	40	42	
September 29....								

COMPARISON OF LOCAL TIME RECORDS AND SEISMOGRAPHIC TIME RECORDS

A comparison of the local time records just quoted with those worked out by Doctor Oldham (page 386) from the seismograph records follows, showing the times of origin determined for inner Yakutat or Disenchantment Bay for the three chief shocks. All are given in Greenwich and in local time.

September 3d Earthquake

P. M. A. M., Sept. 4.

Local record.—3h. 3m. 28s., local solar time; or 0h. 21m. 40s., Greenwich mean time.

Seismograph record.—3h. 2m. 18s., local solar time; or 0h. 20m. 30s., Greenwich mean time.

September 10th Earthquake (the early shock)

A. M.

Local record.—7h. 40m. 0s., local solar time; or 16h. 58m. 12s., Greenwich mean time.

Seismograph record.—7h. 43m. 18s., local solar time; or 17h. 1m. 30s. Greenwich mean time.

September 10th Earthquake (the great Earthquake)

P. M.

Local record.—12h. 22m. 1s., local solar time; or 21h. 40m. 13s., Greenwich mean time.

Seismograph record.—12h. 21m. 18s., local solar time; or 21h. 39m. 30s., Greenwich mean time.

A comparison of these three sets of records shows a close agreement in two out of the three. In the case of the heavy final shock of September 10 the agreement is within 43 seconds, and in the case of the September 3d shock the determinations check within 70 seconds, coming very close to the possible error of "one minute of time" which Doctor Oldham allows himself (page 386). So close a determination must be a source of gratification to Doctor Oldham, as this was probably the first attempt ever made to determine times of origin from distant seismograph records.

The agreement of the two sets of records also accords well with the assumption that the chief shocks on September 3, September 10 and 23 had their principal origins in or near Yakutat Bay. It should be remembered, however, that the rate of transmission assumed, 3 kilometers per second, on which the local time records are based, is wholly arbitrary. The most recent studies of velocity of propagation suggest that a rate of 7 or 8 kilometers per second may have been attained.

SPEED OF TRANSMISSION

An attempt to check the determination of rate of transmission by comparison with the only other local time records of any accuracy, Professor Gwillim's observation near Atlin on September 10, a place almost exactly as far east of Disenchantment Bay as Cape Whitshed is west of there, and Judge Myers' observation at Eagle, about 340 miles north-northwest of Disenchantment Bay, results as follows:

Time of observation, 12h. 45m. 0s. p. m., local solar time near Atlin; latitude of place of observation, near Atlin, 59° 24′ 30″ north; longitude, 133° 35′ 0″ west; latitude of Disenchantment Bay, 59° 58′ 20″ north; longitude, 139° 33′ 0″ west). Correcting this observation for a difference of 23 minutes and 52 seconds of time with 5° 58′ of longitude, we find that the shock appears to have been felt by Professor Gwillim at 12h. 21m. 8s. (Yakutat Bay time), or 53 seconds before it originated at Yakutat.

Similarly a correction of the supposed accurate local solar time observation at Eagle (latitude 64° 13′ north; longitude 141° 15′ west), where the earthquake was felt in the Weather Bureau observatory at 12h. 15m. p. m., results as follows: A correction of 6m. 48s. of time for 1° 42′ of longitude shows that the shock was felt by Judge Myers at 12h. 21m. 48s. (Yakutat Bay time), or apparently 13 seconds before it was generated at Yakutat.

It might be either that (*a*) the time of origin given by us for Yakutat Bay is a minute, more or less, too late, as it would be if we assumed too fast a rate of transmission from Yakutat to the Coast Survey camp at

Cape Whitshed; or (*b*) the determinations of local time by Professor Gwillim and Judge Myers are in slight error, and in each case the observed time comes, suspiciously, on an even five minutes; or (*c*) the chronometer at the Coast Survey camp was not exactly right; or (*d*) there may have been a complex of synchronous origins at other places in the mountains beside Disenchantment Bay. One of the first two explanations is believed to account for the discrepancies. The whole matter is stated thus fully in order to show the futility of any attempt at closer computations based upon the local records at hand.

The speed of transmission for a longer distance, Yakutat Bay to Victoria, British Columbia, is as follows, taking the data from the shock of September 3: Disenchantment Bay, latitude 59° 58′ 20″ north; longitude 139° 33′ west; Victoria, latitude 48° 23′ north; longitude 123° 19′ west. Distance in miles along surface (computed from an 18-inch globe), about 1,000 miles. Time at origin, 0h. 21m. 40s., Greenwich mean time; time at Victoria, 0h. 35m. 9s., Greenwich mean time. Interval for transmission, 13 minutes and 29 seconds, or 809 seconds; 1,000 miles in 809 seconds gives a speed of 1.23 miles, or 2.1 kilometers, per second.

The rate at which the earthquake tremors moved for greater distances is shown in the following table, which is based upon computations by Prof. John Milne[103] on the assumption of an origin in the ocean west of Yakutat, and therefore subject to a slight error.

Speed of large Waves of Three of the Yakutat Bay Earthquakes, in Kilometers per Second.

From Milne's assumed origin, southwest of Yakutat to—	September 3 (Shide No. 333).	September 10 (Shide No. 337), early shock.	September 10 (Shide No. 338), the great earthquake.
Victoria	....	....	....
Toronto	3.4	....	....
Mexico	....	2.3	2.7
Shide	3.2	2.7	2.9
San Fernando	3.1	3.1	3.1
Bombay	3.6	3.6	3.4
Batavia	....	2.9	2.3
Cape Town	3.4	3.5	3.7
Average speed	3.3	3.0	3.0

Average speed of all 17 observations, with origin assumed by Professor Milne, 3.1 kilometers, or almost 2 miles per second.

[103] Fifth Report on Seismological Investigations of the British Association for the Advancement of Science, 1900, plate iii, opposite p. 77.

Professor Milne has also shown that the time necessary for one of these shocks (September 3) to traverse the earth's circumference or two diameters slightly exceeds 210 minutes.[104] This is a rate of about 1.9 miles, or 3.0 kilometers, per second. Doctor Omori made a similar calculation for the September 10th waves,[105] which traveled around the earth with a velocity of 3.6 kilometers per second.

Prof. C. G. Knott[106] has analyzed the relationship of speed of transmission to the location of the paths of the three chief Yakutat Bay earthquakes as follows, on the assumption that the path is not along the chord, but more approximately along the arc. The paths lie as follows:

Victoria	Under sea.
Toronto	Half sea, half land.
Mexico	Half sea, half land.
Shide	Mostly sea, polar archipelago, Greenland?
San Fernando	Half sea and land, largely polar.
Bombay	Mostly land—Siberia, Tibet.
Batavia	Deep sea, east of Asia.
Mauritius	Siberia, India, Indian Ocean.
Cape of Good Hope	Polar sea, Europe, Africa.

Still assuming what we know now to be a slightly erroneous origin and assuming constant speed for small distances and with nine minutes as the time from the origin to Victoria, he made the following table:

Arc.		Chord.	Time of passage in minutes.			Speed.		
						Arc degrees. Min.	Chord. Min.	Arc radians. Min.
Victoria	16°	.28	9	00	00	1.8	.031	.031
Toronto	40°	.68	22	22	22	1.8	.31	.31
Mexico	49°	.83	00	29	28	1.7	.29	.30
Shide	70°	1.15	39	42	41	1.8	.29	.31
San Fernando	77°	1.25	44	44	44	1.75	.28	.305
Bombay	105°	1.59	55	55	57	1.9	.28	.33
Batavia	108°	1.62	00	65	75	{1.66 1.44}	.23	....
Mauritius	145°	1.91	90	00	88	1.63	.215	.284
Cape of Good Hope	165°	1.98	88	89	83	1.9	.226	.33

In the above table $\frac{\text{chord}}{\text{min.}}$ and $\frac{\text{arc radians}}{\text{min.}}$ may be reduced to $\frac{\text{kilom.}}{\text{sec.}}$ by multiplying by 1.06; $\frac{\text{arc degrees}}{\text{min.}}$ may be reduced to $\frac{\text{kilom.}}{\text{sec.}}$ by multiplying by 1.84.

[104] Fifth Report of Committee on Seismological Investigations of the British Association for the Advancement of Science, 1900, p. 69.

[105] Publications of Earthquake Investigation Committee in foreign languages, no. 13, 1903, pp. 121-124.

[106] Fifth Report of Committee on Seismological Investigations of the British Association for the Advancemeent of Science, 1900, p. 77.

Computing these velocities by the above formula, the speed of transmission of surface waves is seen to vary between 3.1 and 3.3 kilometers per second, or nearly two (1.95) statute miles per second, a rate agreeing substantially with those reached independently from the several computations cited above.

DISTURBANCE OF EARTH'S SURFACE

The seismic disturbances traversed the rocks of the earth's crust to all parts of the world from the origin in Yakutat Bay, where Prof. John Milne has estimated that during the faulting one or two cubic miles of rocky material[107] were disturbed and molar disturbances took place.[108] No seismograph known to have been in operation in September, 1899, failed to record these shocks if that type of instrument was capable of registering them.

The disturbances may be divided into two classes: (*a*) those that seismologists infer to have gone directly through the earth, and (*b*) those that follow the earth's outer crust. These are indistinguishable at distances of less than 650 miles. Beyond that distance—for example, at Victoria—the seismograph records show slight disturbances arriving very soon (preliminary tremors) and great motion after a longer time (principal portion or large waves). The preliminary tremors come directly through the earth, along chords. They are generally thought to be longitudinal, compressional vibrations. They have a shorter distance to go and also move at a faster rate than the large surface waves. On September 3, 1899, these direct waves traversed the chord from Yakutat to Victoria in 3½ to 4½ minutes, the large waves, moving presumably along the arc, taking 13 minutes and 29 seconds to reach Victoria through the earth's outer crust.

These large waves of the principal portion vibrate transversely to the line of propagation. They were formerly thought to make the earth's crust actually rise in long, undulating earth-waves. For example, it was estimated[109] that the large waves of the Yakutat Bay earthquake of September 3 passed through Shide, England, as earth-waves about 28 miles in length and 11 2/5 inches high (45 kilometers by 29 centimeters). The earth-waves of the great shock on September 10 at Shide were computed as 74 miles long and 15 2/5 inches high (120 kilometers by 39

[107] Nature, vol. 75, 1907, p. 224.

[108] Seventh Report of Committee on Seismological Investigations of the British Association for the Advancement of Science, 1902, p. 62; Nature, vol. lxvii, 1902-1903, p. 69.

[109] J. Milne: Fifth Report on Seismological Investigations of the British Association for the Advancement of Science, 1900, p. 83.

centimeters), and the waves that followed as about 28 miles long and 17 inches high (45 kilometers by 43 centimeters).

Area disturbed by 1899 Earthquakes

DISCUSSION OF MAPS

Figures 3 and 4 show the minimum area within which the earthquake of September 3 and the great earthquake of September 10 are known to have been felt. The locations of observers are shown by the symbol (*). The outer boundaries are indicated by solid lines only where evidence shows that beyond that line the shocks were insensible. Dotted lines are used as boundaries where information is lacking. If much of this area had not been a nearly empty wilderness in 1899 and if the investigation could have begun at once instead of after seven or eight years, many more of the men who were inside or just outside the shaken area might have been found. Their evidence would surely increase rather than decrease the areas of sensible disturbances for the several earthquake shocks.

Nothing on the maps depends on hearsay evidence. Each symbol represents a reliable observer who has been directly interviewed, or correspended with, or who has replied to an earthquake circular or published an earthquake record in some report.

It is only on the southeast, near Sitka and Sumdum (figure 4); on the north, near Dawson, Circle, and Rampart, and on the west, between Seldovia and Kodiak, that even partial outer boundaries could be drawn. In other directions the shocks were probably sensible even farther than shown, for they were felt everywhere along a chance line of points of observation like the Klondike trail, to the east of which there were probably no human beings in 1899.

One reason for incompleteness of data is that at distances of over 250 miles these shocks were often so weak as to be imperceptible to persons engaged in one occupation, while to others they were sensible. At Sitka, for example, the great earthquake of September 10 was felt by Bishop Rowe, who was lying down, but not by Doctor Georgeson, who was walking out of doors. Two hundred and fifty miles northwest of Yakutat Messrs. Brooks and Peters, of the U. S. Geological Survey, did not feel the September 3d earthquake, though they heard the boom of avalanches caused by it and at exactly the proper time. These men, though trained scientific observers, did not feel the great earthquake of September 10, probably because they were on the march. These shocks were felt, however, 60 miles farther from Yakutat, along the same line, jarring apparatus and causing lamps to swing in the U. S. Weather Bureau office at Eagle and being observed by prospectors panning gold in the Forty-Mile district.

Local topographic or geological conditions also explain observation or failure at great distances. In the Koyukuk and lower Yukon observations (shown on figure 3 as detached areas) weak tremors seem to have been naturally amplified in the unconsolidated Pleistocene silts.

SQUARE MILES SHAKEN

The shocks of the great earthquake on September 10 (figure 4) were felt at all places within 250 miles of Yakutat and at other points up to 480 miles from the origin. This minimum area of sensible shocks includes 216,300 square miles on the land alone, and if an equal area in the Pacific Ocean was disturbed (figure 1) the minimum area includes 432,500 square miles. This takes no account of the detached observation on Lake Chelan, Washington.

The observations by Mr. Schrader on the Koyukuk and by Father Amcan on the lower Yukon are detached areas beyond the compact minimum area of the shock of September 3 (figure 3). If these points, 670 and 730 miles respectively from Yakutat, were included, together with other points equally distant, a circular area with a radius of 700 miles was shaken, and this area included about 1,539,000 square miles. This is considered quite probable, first, because this part of Alaska was, in 1899, an almost vacant wilderness, and, secondly, because people in Alaska become so accustomed to earthquakes that they do not notice or record weak tremors at great distances like these. In Alaska, too, there were no high buildings to naturally amplify weak tremors not sensible to persons on the ground, as was the case in La Crosse, Wisconsin; Boston, Massachusetts, and New York City[110] during the Charleston earthquake of 1886.

The inclusion of the disturbed areas within circles follows the assumption that Yakutat Bay was the center of disturbances, outside of which there was little or no movement. This hypothesis seems warranted, in the absence of other evidence, and the plotting of the minimum areas (figures 3 and 4) bears this out somewhat. An alternate hypothesis would consider the tectonic disturbances to extend in the direction of the axis of the Saint Elias-Chugach range. Facts are not available for settling absolutely between these hypotheses.

[110] C. E. Dutton: Ninth Annual Report of the U. S. Geological Survey, 1889.

Relation to other Alaskan Earthquakes

Alaska has been classified as only peneseismic by Comte F. de Montessus de Ballore,[111] who says that "the only important earthquake known is that of September, 1899, at Yakutat Bay." There are other severe earthquakes, however, and the same seismologist, after cataloguing 131,292 earthquakes and 10,499 epicenters up to the end of 1897, assigns 12 earthquakes to 7 epicenters in Alaska and 86 earthquakes to 15 epicenters or localities so considered in the Aleutian Islands[112] (figure 9).

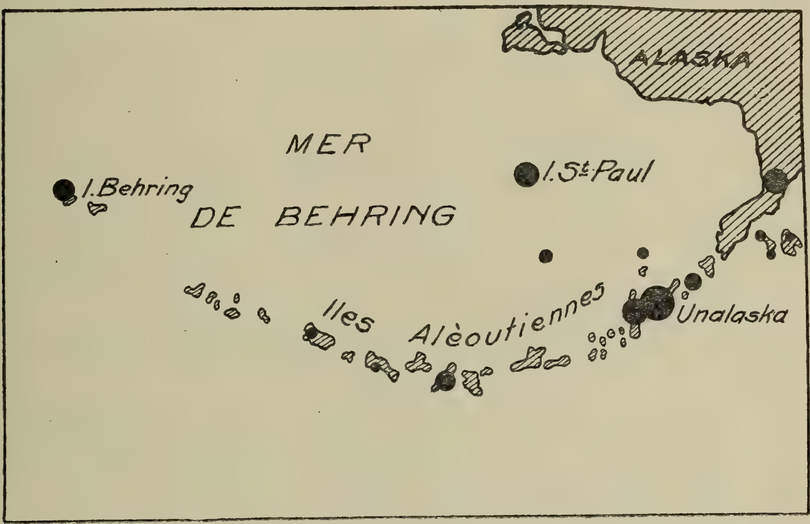

Figure 9.—*Habitual Epicenters in Aleutian Islands and Bering Sea* (after de Montessus de Ballore)

These shocks are presumably chiefly volcanic rather than tectonic

Dr. G. K. Gilbert credits Alaska with nine shocks of destructive rank[113] since the beginning of the last century, stating that the record is fragmentary and may omit more than it includes.

The first recorded earthquake in Alaska is that stated by Grewingk[114] to have occurred in the Sannak and Shumagin islands, south of the

[111] Les Tremblements de Terre, Paris, 1906, p. 414.

[112] Introduction à un essai de description sismique du globe et mesure de la sismicité. Beiträge zur Geophysik, band iv, p. 363.

[113] Earthquake forecasts, Science, N. S., vol. xxix, 1909, pp. 125-126.

[114] C. Grewingk: Treatise on the volcanic character of certain regions of the Russian possessions. Proceedings of the Mineralogical Society of Saint Petersburg, 1850; translated by Ivan Petroff in Report on seal and salmon fisheries and general resources of Alaska, Senate Document 59, 45th Congress, 1st session, p. 313; House Document 92, 55th Congress, 1st session, part iv, p. 313; Tenth Census, 1880, vol. 8, pp. 95-96.

Alaska Peninsula, in 1788, when "there were no volcanic phenomena reported, but on the 27th of July a flood submerged the islands of Sannak and Ounga and a portion of the peninsula (evidently a tidal wave, owing to earthquake)." Dall[115] states that during this inundation many natives lost their lives and that hogs on Sannak Island were drowned.

Grewingk,[116] Perret,[117] and Dall[118] have listed earthquakes, mostly in connection with volcanic eruptions, in 1790, 1792, 1796, 1802, 1812, 1817, 1818, 1820, and 1826. In 1827 there was an earthquake on Copper Island in June, but it is not stated whether in association with a volcanic eruption or not. On April 2, 1836, and in August of the same year earthquakes were felt on the islands of Saint Paul and Saint George, in the Pribilof group, during which it was impossible to stand erect.

In 1843 occurs the first precise scientific observation of a tectonic earthquake in Alaska instrumentally recorded that has come to the writer's attention. This is quoted by Perret, from whose account[119] the following is translated:

> "On the 15th of December, at 1.20 a. m., there were two light shocks on Sitka Island, during which the unifilar and bifilar magnetometers oscillated in a vertical plane.
>
> "There was a second shock an hour and twenty-five minutes later. The position of the vertical-force needle changed 55 parts during the first two shocks."[120]

On December 16, 1843, at 1.30 p. m., there was a feeble earthquake at New Archangel (Sitka). At 4 p. m. there was a stronger shock, lasting three seconds; the houses were rent; the workman saw the trees apparently move back and forth during a calm. At the warm springs, 28 versts from the town, other persons observed these shocks, but 35 minutes earlier.[121]

In 1847 a general earthquake was felt on the Alaskan coast, being very severe at Sitka.[122] This is doubtless one of the shocks referred to by the newspapers of 1899, which allude to the Yakutat Bay earthquakes as "the most severe since the time of the Russians."

On October 22, 1849, there was a violent earthquake, lasting all night,

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115 W. H. Dall: Alaska and its resources. Boston, 1870, pp. 310, 467.

116 Op. cit., pp. 311-315.

117 Alexis Perret: Documents sur Les Tremblements de Terre et Les Phenomenes Volcaniques des iles Aleutiennes, de la peninsule d'Aljjaska et de la cote No. d'Amerique. Acad. Imp. de Dijon, deuxieme serie, tome xiii, 1865, pp. 158, 216-237.

118 Op. cit., pp. 466-470.

119 Alexis Perret, Mem. Acad. Imp. de Dijon, 2me. ser., tome xiii, 1865, p. 238.

120 Annuaire magnétique et météorologique du corps des ingénieurs des mines de Russie, année 1843, p. 553.

121 Comm. de M. Osten-Sacken.

122 W. H. Dall: Op. cit., p. 342.

in the Commander Islands. This is listed by Alexis Perret,[123] as are the succeeding earthquakes of 1853, 1857, 1859, 1861, and 1866.

On November 13, 1853, about 100 kilometers[124] east of Ikogmute, on the lower Yukon, there was a shock at the village of Paimüt, moving from south to north. Earthquakes there are infrequent, the last having been felt sixty years before. The above note is from a meteorological register then kept at Ikogmute by P. Netzvetor.[125]

On September 8, 1857, at 11 a. m., two earthquakes were felt at Saint Paul (now called Kodiak), on Kodiak Island. They were several seconds apart, the second being rather severe, though no damage was done.

On August 8, 1859, there was a light shock, lasting several seconds, on Bering Island.

Sitka was again shaken by an earthquake on April 21, 1861, at 9.36 a. m.[126]

On May 3, 1861, there was a light shock on Saint George, Pribilof Islands, with a subterranean noise. There was a light shock on Atka Island at 8.30 a. m., on May 10, 1861, followed by another on August 21, this last with a subterranean noise.[127]

In 1866, and before October 22 of that year, there was an earthquake near Kodiak. Further details are lacking.

In 1867 an earthquake was felt at Russian Mission (Ikogmute), on the lower Yukon, where the shock of September 3, 1899, was also felt, and near which was recorded the shock of 1853 and another sixty years before. W. H. Dall[128] was on the Yukon River at about 11 o'clock on the night of July 19, and reports that it felt as if the boat had struck a snag. This has also been reported by Frederick Whymper.[129] The shock was severe enough at the mission to throw books and other articles from the shelves.

In 1868 Becker[130] states that "during a slight earthquake the elevation is said to have amounted locally at Unga to over 20 feet."

Petroff[131] mentions a violent earthquake at Sitka in the autumn of 1880.

[123] A. Perret: Op. cit., pp. 239, 243, 244, 246, 247, 251.

[124] Really only 38 miles.

[125] M. Vesselofski, Permanent Secretary of Academy of Sciences, Saint Petersburg.

[126] Ann. meteor. et magn. de Russie, 1861, p. 455.

[127] Notes extraites du comte-rendu de la Compagnie russe-américaine pour 1861, par M. le baron Osten-Sacken.

[128] Alaska and its resources. Boston, 1870, pp. 118, 470; The Yukon Territory, London, 1898, p. 118.

[129] Journal of the Royal Geographical Society, London, vol. xxxviii, 1868, p. 234. Travel and adventure in the Territory of Alaska, New York, 1869, p. 266.

[130] G. F. Becker: Reconnaissance of the gold fields of southern Alaska. Eighteenth Annual Report, U. S. Geological Survey, part iii, 1896-1897, p. 19.

[131] Ivan Petroff: Alaska, its population, industries, and resources. Tenth Census of the United States, 1880, vol. viii, p. 91.

In 1883 there are said[132] to have been earth tremors and a 30-foot water wave in Cook Inlet in connection with an eruption of the Saint Augustine volcano there. This was on October 6, 1883.

Deckert shows many of the earthquakes referred to above on his map of earthquakes in North America,[133] and in addition lists three earthquakes in the Aleutian Islands in 1877, 1878, and 1879, all presumably volcanic shocks. A fourth was felt at Kodiak in 1889.

F. G. Plummer's list of earthquakes on the Pacific coast,[134] as reprinted by E. S. Holden,[135] contains nearly all of the earthquakes thus far cited and a few others, most of them in connection with volcanic outbursts, as during the eruption of Pauloff in 1786; at Kaviak in 1854; at Black Peak, near Chignik, on August 28, 1892; at Unalaska, September 23, 1892, and on Saint Augustine volcano in the summer of 1893.

Several of the Alaskan shocks referred to above are also recorded in the yearly lists of Pacific Coast earthquakes from 1888 to 1898 by E. C. Holden,[136] T. F. Keeler,[137] and C. D. Perrine.[138]

There have doubtless been many other earthquakes in Alaska, but no list or description of them is available. The Russian records of various sorts are a great unused storehouse of information of this kind. The records of the voluntary Weather Bureau observers of the U. S. Department of Agriculture doubtless also contain much information concerning other earthquake shocks in Alaska at various places and times between the time of the American purchase of Alaska and the end of the century.

In connection with the gathering of information concerning the seismic disturbances of 1899 at Yakutat, which are the subject of this paper, a considerable amount of unpublished data has come into my hands concerning other earthquakes in Alaska. I have thought it best briefly to summarize this, both because it enables me to place the Yakutat Bay shocks of 1899 in their proper setting as a series of especially severe tectonic shocks in an earthquake-shaken region, where there are both tectonic and volcanic earthquakes, and because I feel that this information, fragmentary and incomplete as it is, should be placed on record for the use of those interested in seismology. In 1901 a magnetograph was

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132 George Davidson: Science, vol. iii, 1884, pp. 186-189.

133 E. Deckert: Zeitschrift der Gesellschaft für Erdkunde zu Berlin, 1902, Tafel 5 and pp. 367-389.

134 Reported earthquakes on the Pacific coast. Publications, Astronomical Society of the Pacific, vol. viii, 1896, p. 78.

135 A catalogue of earthquakes on the Pacific coast, 1769 to 1897. Smithsonian Miscellaneous Collections, 1087, vol. xxxvii, 1898, pp. 1-253.

136 American Journal of Science (series 3), vol. 37, 1889, pp. 392-402. Bulletin no. 95, U. S. Geological Survey, 1892.

137 Bulletin no. 68, U. S. Geological Survey, 1890.

138 Bulletins nos. 112, 114, 129, 147, 155, 161, U. S. Geological Survey, 1893 to 1899.

installed by the U. S. Coast and Geodetic Survey at Sitka, and on April 29, 1904, a Bosch-Omori seismograph, so that in the future the earthquake records from Alaska will be fairly complete.

In the preceding list the earthquakes reported by Grewingk, Perret, Dall, Petroff, and Becker in 1788, 1843, 1847, 1853, 1857, 1861, 1866, 1867, 1868, and 1880 are doubtless tectonic. Some may have been world-shaking. The others are doubtless largely volcanic and merely local.

Other tectonic shocks in Alaska which were probably world-shaking, like these in Yakutat Bay in 1899, and which have not previously been described, are mentioned below. There were no volcanic phenomena of Mount Wrangell or the Aleutian volcanoes at these times.

The Chugach earthquake of October 9, 1900, was felt between 2 and 3 a. m. in the Chugach Mountains and all about the Gulf of Alaska from Yakutat Bay to Kodiak Island. The minimum area disturbed was about 121,000 square miles on the land. The seismograph stations at Victoria and Toronto recognized its Alaskan origin, and instruments throughout the world recorded it.[139] The seismograph record was referred to by Prof. John Milne,[140] and seismograms at Laibach, Austria,[141] and Tokio, Japan,[142] have been published. The latter is reproduced in this article as the upper seismogram in plate 30.

The Lynn Canal earthquake of September 24, 1907, was felt at Skagway at 4.02 a. m., and at Sitka at 3.59½, where the U. S. Coast and Geodetic Survey seismograph recorded it.

The Prince William Sound earthquake of February 14, 1908, was felt at Valdez about 1.25 a. m.; also throughout Prince William Sound and eastward to Controller Bay. Two submarine cables in Valdez fiord were broken by faulting in 600 to 700 feet of water. Seismographs recorded this shock at Sitka, Victoria, Toronto, Baltimore, etcetera.

The Controller Bay earthquake of May 14, 1908, occurred at 11 p. m., and was sensible along the Alaskan coast from Seward to Sitka. Seismographs recorded it at Sitka, Victoria, Toronto, Baltimore, Cheltenham, Washington, Porto Rico, the Hawaiian Islands, and doubtless elsewhere. Other Alaskan earthquakes are mentioned in the following list.

The place of observation was not usually, of course, the origin of the earthquake, and it is not known how many of these shocks are volcanic and how many tectonic. Many of the places referred to here are shown on figure 8.

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[139] Seismological Committee of the British Association for the Advancement of Science, circular 3, 1901, pp. 63, 65, 69, 73, 74, 77, 85, 87, 89.

[140] Nature, vol. lxv, 1902, p. 203.

[141] Beiträgen zur Geophysik, Ergänzungsband I, 1902, tafel v, fig. 13.

[142] Publications of Earthquake Investigation Committee in foreign languages, no. 21, 1905, fig. 51.

Observers.	Places.	Years.	Dates.	Remarks.
T. G. White	Yakutat	1893.	March	
R. W. Beasley	Yakutat	1894.	November 3.	Three light shocks.
John Shepard	Orca	1896.	May	Very severe; earthwaves.
R. W. Beasley	Yakutat	1897.	January 11	Severe, shaking the house.
C. P. Coe	Wood Island		Winter	7 p. m.
H. H. Pitts	Selkirk		May 6	Buildings vibrated and gravel slid in river banks.
Prospector	Tyonek	1898.	About Aug. 15	Slight.
Rev. F. R. Falconer	Susitna Station		August	Trees swayed violently on calm, windless day.
Charles Brown	Valdez		August 24	Heavy earthquake at 10 p. m.
J. E. Spurr	Katmai		October 15	Near Hot Springs.
Oscar Rohn	Katmai		October	
F. E. Fuller	Skagway		Oct'r–Nov'r	7.30 a. m., slight.
S. S. Sharick	Juneau			Northeast, 15 seconds; 15 minutes later, 8 to 10 seconds.
H. S. Tibbey	Unga	1899.	March 18	Four seconds, motion west to east.
H. S. Tibbey	Unga		April 1	4.45 p. m., east to west. Threw light articles off shelves.
H. S. Tibbey	Unga		June 8	10 a. m., north to south, light.
H. S. Tibbey	Unga		July 14	2.55 a. m. Two shocks north to south, 6 seconds, rumbling noise preceding.
Prospector	Tyonek		July 11	Severe.
W. A. Sawtelle	Unalaska		July 14	2.15 a. m.
H. S. Tibbey	Unga		Sept'r 22	9.30 p. m., severe, north to south.
Capt. J. S. Herron	Alaska Range		Oct'r 21–22	Shocks, with low, rumbling noises.
C. K. Corbusier	Tanana			Bottles rattled on shelf, same at Fort Gibbon.
Capt. R. McCoy	Fort Gibbon		November 1.	11.05 p. m.
L. S. Camicia	Valdez	1900.	July 30	1 p. m.
R. W. Beasley	Yakutat		August 7	4.15 p. m., light.
R. W. Beasley	Yakutat		August 8	5.25 p. m., light.
R. W. Beasley	Yakutat		August 9	7.40 p. m., light.
R. W. Beasley	Yakutat		August 9	11 p. m., light.
August Groot	Cross Sound, 80 miles west of Juneau.		August	Light shocks.
Prospector	Tyonek		October 7	Severe shock.
T. G. White	Katalla		October	
L. L. Bowers	Kodiak		October 11	
L. L. Bowers	Kodiak		October 12	5.15 a. m.
H. P. Cope	Kodiak		October 13–14	
C. P. Coe	Wood Island		October 14	
L. L. Bowers	Kodiak		October 14	2.30 and 5.15 a. m.
L. L. Bowers	Kodiak		October 15	8 and 8.15 a. m.
L. L. Bowers	Kodiak		October 22	During evening.
L. L. Bowers	Kodiak		October 23	3 a. m.
L. L Bowers	Kodiak		October 24	Slight shocks during day.
L. L. Bowers	Kodiak		October 26	Slight during day and night.
R. W. Beasley	Yakutat		December 17	5 a. m.
L. L. Bowers	Kodiak		December 27	12.05 a. m., short and heavy.
R. W. Beasley	Yakutat		December 31	1.40 a. m.
H. W. Mellen	Prince of Wales Island.		Fall 1900, spring 1901.	Frequent rumbling noises and light tremblings.
L. L. Bowers	Kodiak	1901.	January 17	8.30 a. m.
R. W. Beasley	Yakutat		January 19	7 a. m.
R. W. Beasley	Yakutat		January 24	5 a. m.
Capt. R. McCoy	Fort Gibbon		March (?)	Hard earthquake.
L. L. Bowers	Kodiak		April 4	6.30 a. m.
L. L. Bowers	Kodiak		May 30	7.15 p. m., light.
G. F. Baker	Fairbanks		July 12.	8.30 a. m.
L L. Bowers	Kodiak		July 23	4.25 p. m.
Simeon Post	Valdez		September	
L. S. Camicia	Valdez		September	2.50 p. m.
R. W. Beasley	Yakutat		Sept'r 28	12.30 p. m.
Adolph Stecker	Bethel	1902.	February	
Prospector	Tyonek		April 18 or 19	Slight.
Brother Constantine	Koserefsky		December 6	Thought building would be crushed.

Observers.	Places.	Years.	Dates.	Remarks.
Rev. A. R. Hoare	Tanana		Winter 1902–1903.	
R. W. Beasley	Yakutat	1903.	March 10	6. a. m.
J. H. Robinson	Eagle		Spring	
Chas. Suironstad	Valdez		March	Drove people into streets.
W. A. Dickey	Landlock		May	
L. S. Camicia	Valdez		June 2	3.45 p. m., strong shock; direction, northeast to southwest.
L. S. Camicia	Valdez		July 13	11.40 a. m.
G. C. Martin	Dry Bay		July	Cliffs fell.
G. C. Martin	Enochkin Bay		August	Waves on still water of bay.
L. N. Gordon	Seward		1903	Very severe.
R. W. Beasley	Yakutat		Sept'r 10	5 a. m.
Brother Constantine	Koserefsky	1904.	December 8	Violent shaking of log church.
Dr. J. H. Romig	Nushagak		1904–1905	
L. S. Camicia	Valdez	1905.	February 6	7.20 a. m.
E. E. Ritchee	Seward		August	20 to 30 seconds.
L. S. Camicia	Valdez		November 22	At midnight.
Rev. N. N. Amcan	Onhagmute		December 8	
Adolph Stecker	Bethel		December 9	
Rev. John Hinz	Ogavik, Kuskokwim.		December 8	House rocked; also felt 80 miles away at Bethel.
L. S. Camicia	Valdez	1906.	May 25.	5 a. m.
Mrs. J. R. Heckman	Loring		August 6–7	10 p. m. and 3 a. m.
R. S. Tarr	Yakutat Bay		Summer	Slight tremors.
J. R. Hayden	Fairmont Island		Sept'r 19	2 p. m.
L. S. Camicia	Valdez		October 25	2 10 a. m.
J. J. Tolbert	Dutch Harbor		November 28	Slight, 12.30 a. m.
J. J. Tolbert	Dutch Harbor		December 20	Slight, during day.
C. L. Boudry	Cold Bay		December 25	7 a. m.
J. J. Tolbert	Dutch Harbor		December 22	7 a. m. and 7.55 p. m.
C. L. Boudry	Cold Bay		December 28	10 p. m.
Judge Lars Gunderson	Mary's Igloo, Hot Springs, and Shelton.		March	
J. J. Tolbert	Dutch Harbor	1907.	August 22	11.25 a. m.
Dr. J. H. Romig	Nushagak		1906–1907	
Dr. J. H Romig	Nushagak		September 6.	
S. Kilborn	Killisnoo		October 5	Light shocks.
J. R. Hayden	Prince William Sound.		Fall	
J. D. Jefferson	Valdez		December 10	
Lieut. L. H. Hansen	Fort Liscum	1908.	May 3	7 p. m., 10 seconds.
Lieut. L. H. Hansen	Fort Liscum		May 4	7.35 a. m., 15 seconds, slight shock, with rumbling sounds.
L. S. Camicia	Valdez		May 4	7 a. m.
Rev. N. N. Amcan	Kuskokwim River		June 8	
J. J. Tolbert	Dutch Harbor		March 15	Three shocks, one at 3 o'clock and two about 7.
B. F. Baker	Hot Springs		December 20	6 a. m., sharp shock.
E. A. Rasmussen	Yakutat	1909.	February 16.	Stopped clocks.
E. A. Rasmussen	Yakutat		May 6 (?)	Spilled water out of reservoir on stove and from barrels outdoors.
Lawrence Martin	Russell Fiord, Yakutat Bay.		July 16	Slight, with booming noise, as of avalanche.

Comparison with other Great Earthquakes

The Yakutat Bay earthquakes of September, 1899, are in some respects like and in some respects different from other great seismic disturbances. They rank among the greatest North American earthquakes (figure 1) and stand high among the world's seismic disturbances in intensity and area affected. The following is a list of the areas affected by some of the larger tectonic earthquakes of historic times:

Charleston, 1886, about 2,800,000 square miles:

Felt at La Crosse, Wisconsin, Boston, Massachusetts, Cuba, and Bermuda. Maximum radius of propagation, 700 to 950 miles.

Lisbon, 1755, about 2,240,000 square miles:[143]

Felt in Great Britain, throughout western Europe, and in northern Africa. Maximum radius of propagation, 700 to 1,200 miles.

India, 1897 (Assam), about 1,750,000 square miles:

900-mile radius of propagation.

Alaska, 1899, about 1,539,000 square miles:

700 (670 to 730) mile radius of propagation. (Minimum land area, 216,300 square miles; land and sea area, about 432,500 square miles.)

India, 1905 (Kangra), about 1,500,000 square miles.

New Madrid, 1811-1812, about 1,250,000 square miles:

Felt at Charleston, South Carolina, Richmond, Virginia, Washington, District of Columbia, Louisville, Kentucky, Fort Duquesne (Pittsburg), Detroit, Fort Dearborn (Chicago), etcetera.

Sonora, Mexico, 1887, about 500,000 square miles:

Felt at Durango, Mexico, Fort Davis, Texas, Las Vegas and Santa Fe, New Mexico, Prescott and Yuma, Arizona, and generally within about 400 miles.

California, 1906, about 372,700 square miles:

Felt in Coos Bay, Oregon, Los Angeles, California, and Winnemucca, Nevada. Radius of propagation, 350 to 400 miles.

Japan, 1891, about 330,000 square miles:

Radius of propagation, 323 miles.

Riviera, 1887, about 219,000 square miles:

Radius of propagation, 264 miles.

In connection with the Yakutat Bay, Alaska, earthquakes of September, 1899, there were physical changes, including submergence, as in the Indian earthquake of 1819 and the Jamaica earthquakes of 1692 and 1907. There was elevation, proved by uplifted beaches, cliffs, sea caves, and marine animals attached to the rocks, as in Darwin's South American earthquakes of 1822, 1835, and 1839. No other historic earthquake beside that of Alaska reveals an uplift of as much as 47½ feet at one time. There were new reefs, as in the New Zealand earthquake of 1855. There was surface faulting, as in the Calabrian earthquake of 1783, the New Madrid earthquakes of 1811-1812, the Owens Valley earthquake of 1872, the Mexican earthquake of 1887, the Japanese earthquake of 1891, the earthquake of 1896 in Iceland, the Indian earthquakes of 1897 and 1905, and the San Francisco earthquake of 1906. There was disturbance of surface and underground drainage, with formation of sand vents and craterlets, as in the Charleston earthquake of 1886, as well as several listed above. There were destructive water waves, or tsunami, as in the Lisbon earthquake of 1755, the Japanese earthquake of 1896, and others.

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[143] Perhaps 500,000 square miles less; Oldham (Memoirs, Geol. Survey of India, xxix, 1899, p. 376) says perhaps only 1,000,000 square miles.

The glacial oscillations which have resulted from these Yakutat Bay earthquakes, including the initiation of the eight-mile retreat of Muir Glacier and other ice-tongues of Glacier Bay, and the great spasmodic advances of part of the Malaspina and at least six other glaciers in Yakutat Bay, find no known parallel among the world's historical earthquakes. These advances, however, explained by abnormal accession to the glacier reservoirs through earthquake avalanches, must surely find a parallel in other regions of lofty, snow-capped mountains which are still so young as to be frequently faulted and shaken by earthquakes. Future studies of earthquakes in Alaska, the Alps, the Caucasus, the Himalayas, etcetera, will probably reveal such glacial oscillations.

Relation of Yakutat Bay Earthquakes to Life

In contrast with practically all the great earthquakes of historic times, the Yakutat Bay shocks of September, 1899, stand conspicuous for the absence of loss of life and destruction of property which accompanies most seismic disturbances. This was because they took place in an area largely wilderness at that time and because the frontier inhabitants lived in tents, in log cabins, or in low frame buildings. The minimum land area shaken by the great earthquake of September 10 (216,300 square miles, figure 4) contained a population of 20,000 persons or less.[144]

In 1891, during the earthquake in Japan, 7,279 people were killed and 17,393 injured, 197,000 buildings were destroyed and 84,000 damaged. Twenty-seven persons lost their lives in the Charleston earthquake of 1886, 56 others perishing by cold, exposure, etcetera, out of a city of 50,000 to 55,000. Many houses were destroyed, many more damaged, and 13,000 chimneys thrown down. In the first (Assam, 1897) Indian earthquake practically all the buildings in 145,000 square miles were laid in ruins. In the second (Kangra, 1905) Indian earthquake 18,815 lives were lost, and the destruction of property was enormous, the number of buildings destroyed being 112,477. In California,[145] in 1906, between one and two hundred thousand people were made homeless, but only 709 lives were lost directly because of the earthquake. There was tremen-

[144] Twelfth Census of the United States, vol. i, p. 426, shows 11,668 in the disturbed area in Alaska out of 63,592, the total population of Alaska in 1900. The Atlas of Canada, pp. 4 and 13, shows 8,935 persons in the shaken part of Yukon Territory in 1901, the number in the shaken part of British Columbia not being given. Presumably the population was nearly as great in the two previous years, although there may not have been the same number of gold-seeking prospectors in 1899 as in 1900 or 1901.

[145] G. K. Gilbert: Science, N. S., xxix, 1909, p. 137.

R. L. Humphrey and Frank Soulé: The San Francisco earthquake and fire, Bulletin 324, U. S. Geological Survey, 1907, pp. 61 and 138.

A. G. McAdie: Catalogue of earthquakes on the Pacific coast, 1897 to 1906, Smithsonian Miscellaneous Collections, vol. xlix, 1907, p. 47.

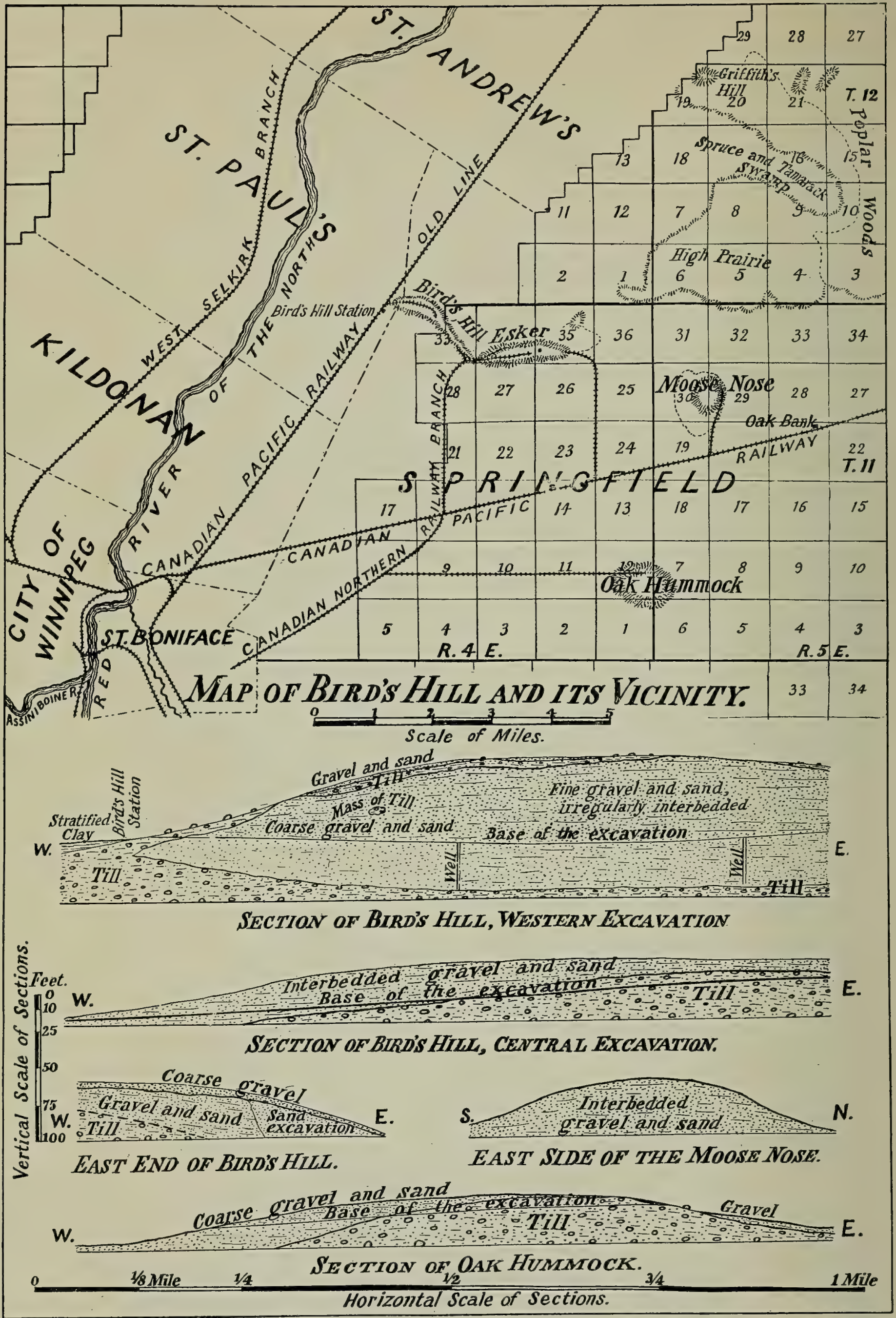
dous destruction of structures, 25,000 buildings being destroyed in the earthquake and fire, with an estimated value of between 139 million and 500 million dollars. In the Riviera earthquake, in 1887, 640 people were killed and over 570 injured, 155 houses were rendered uninhabitable in Mentone, 61 in Nice, and many others elsewhere, so that the property loss was over $5,000,000. Lyell states 60,000 people were killed in six minutes in the Lisbon earthquake of 1755, practically the whole city being thrown down. About 20,000 lives were lost in the Calabrian earthquake of 1688, about 43,000 in 1693, between 32,000 and 60,000 in 1783, 800 in 1905, while the loss of life in 1908 was stated as 100,000.

In contrast with all this, there was no recorded loss of life as a result of the Yakutat Bay earthquakes, and the most serious property damage known, aside from the loss of a rowboat, some tents, provisions, and clothing by the eight prospectors in Disenchantment Bay, was the shifting of the roof of an uninhabited log cabin in outer Yakutat Bay and the cracking of a few chimneys and slight damage to a wharf in Skagway. The great earthquakes of New Madrid, Sonora, South America, and New Zealand, likewise in rather thinly populated districts, would doubtless be more like the Alaskan case in slight damage to the human race.

In Yakutat Bay lower forms of life, particularly marine animals and plants, were destroyed by millions. Many fish were killed by the shocks or washed up by the water waves. Annual land plants and forest trees were killed by the water waves or by submergence of the coast. Human life, however, was almost unaffected, excepted through nervous strain.

The Yakutat Bay earthquakes of September, 1899, do not contribute to the problems of warning and safety for the human race during the seismic disturbances accompanying earth movements. They are in the unfortunately small class of world-shaking disturbances of which one may read without turning with a shudder at the loss of human life.

Evidences of older faulting, older uplifts, older submergences, and older earthquakes in Yakutat Bay lead to the expectation of future earthquakes there from future earth movements in this growing mountain range. The region has few inhabitants, nor is it likely to be much visited except as its wonderful glaciers (figure 5) attract tourists, especially now that the well known Muir glacier has lost much of its scenic interest. Future earthquakes, therefore, are not likely profoundly to influence life, as would be the case if Yakutat Bay and other parts of Alaska were thickly populated as are such earthquake regions as Japan, India, the East Indies, Asia Minor, the Balkan Peninsula, Italy, Spain, the West Indies, western South America, Mexico, and California.



MAP AND SECTIONS OF BIRDS HILL, MOOSE NOSE, AND OAK HUMMOCK, NEAR WINNIPEG, MANITOBA

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BIRDS HILL, AN ESKER NEAR WINNIPEG, MANITOBA[1]

BY WARREN UPHAM

(Presented by title before the Society December 29, 1909)

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INTRODUCTION AND TOPOGRAPHIC DESCRIPTION

Last August, during the meeting in Winnipeg of the British Association for the Advancement of Science, an excursion by 16 of the geologists in attendance was taken for examination of the esker named Birds Hill, adjoining the station and little village of Birds Hill, 8 miles northeast of Winnipeg, on the old and original main line of the Canadian Pacific Railway. This esker, a ridge of sand and gravel, extensively excavated for building and street uses, has a length of about 4 miles to the southeast and east from that station. Both the old line of the Canadian Pacific Railway and its newer line on the south have spur tracks or short branch lines for bringing the sand and gravel from the many and long excavations by which much of this esker at each end and along the greater part of its course is being removed for economic purposes.

The height of the esker is mostly 40 to 50 feet above the level of the very flat Red River Valley plain. Its width, including the generally

[1] Manuscript received by the Secretary of the Society December 30, 1909.

smoothly rounded top and the moderately steep or mostly very gentle slopes on each side, ranges from 500 to 1,500 feet, being mainly about 1,000 feet. Thus it differs from a majority of eskers in being broader and lower and in having less steep sides than the average type of its class of drift formations.

Because Birds Hill is the nearest plentiful source of builders' sand and gravel ballast for construction in the large and fast growing city of Winnipeg, its excavated sections are freshly and clearly exposed to view, with relatively little obscuration by falling talus slopes. The excavations now are several times greater than in 1887, when I first examined this gravel ridge, during my surveys of the Glacial Lake Agassiz. It then seemed to me exceedingly interesting and instructive, so that a small map, showing the esker and its vicinity, and a section along its earliest excavation, already reaching nearly three-fourths of a mile eastward from Birds Hill Station, were presented in my reports of that glacial lake.[2] But the observations made in August and September, 1909, on the British Association excursion, and in two later trips, have enabled me to learn the structure, geographic and geologic relationship, and the significance of this very remarkable esker far more satisfactorily than before.

Origin of the Name

A pioneer settler, Dr. J. C. Bird, widely known as a skillful physician, who lived many years in Saint Pauls township or parish, on the west side of the Red River, opposite to this hill, is commemorated in its name, which later was applied to the railway station when this first railway traversing Manitoba was built. Doctor Bird was elected a member of the first Legislature of Manitoba, in 1870; was speaker of the House from February 5, 1873, to the end of that Legislature, in 1874, and was reelected for Saint Pauls in the general elections of that year. He died in England in 1876.[3]

This dry, sandy esker ridge was often visited in the early spring and during the summer by Doctor Bird, and likewise by Hon. James W. Taylor, the United States consul in Winnipeg, 1870-1893, for gathering its wild flowers, including the pasque-flower, the earliest in spring, and many other species which are common on the esker but are rare or absent on the surrounding level and mostly clayey country.

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[2] Geological and Natural History Survey of Canada, Annual Report, new series, vol. iv, for 1888-89 (published in 1890), part E, pp. 38-40, with a section.

U. S. Geological Survey Monograph xxv, 1895, pp. 183-187, with map and section.

[3] History of Manitoba, by Robert B. Hill, 1890, p. 764.

Only one house has been built on the esker, this being the summer home of E. F. Hutchings, of Winnipeg, about 3 miles east from Birds Hill Station. The part of the esker there and for a half mile or more to the west, commanding a broad and beautiful prospect of the flat valley plain to the south and north, 50 to 60 feet below, was named Lorne Hill about 30 years ago, on the occasion of a visit by the Marquis of Lorne, Governor of Canada; but this name seems not to have come into general use. Instead, the earlier name Birds Hill, which originally was applied to the most western mile of the esker, separated by a lower part from its prominent development for more than a mile adjoining the summer residence of Mr. Hutchings, is now commonly bestowed on the whole length of this esker. Such usage of the name is promoted by the recent opening of a large excavation or pit by the Birds Hill Sand Company in the east end of the esker, from which the best grades of sand are obtained in large quantities for masons' use in mortar and plaster, and for the tempering of clay by the brickmakers of Saint Boniface and Winnipeg.

Structure of Birds Hill

Along the distance of almost a mile from its west end the esker rises to a height of 40 to 50 feet, and has an east-southeast course, with a width of a sixth to a quarter of a mile. Its central third or two-fifths, from near its crest northward, through a length of about 4,000 feet, has been removed for railway ballast, masons' use, etcetera, by steam shovels and by hand work, loading on cars of a spur branching from the Canadian Pacific Railway at Birds Hill Station. The elevation of the station is 759 feet, and of the crest of the ridge 800 to 810 feet, above the sea. On the southern side the section ranges from 30 to 50 feet in depth from the natural surface, and on the northern side from 20 to 25 feet.

As thus exposed to view, the greater part of this deposit is seen to be gravel, some of which is very coarse, containing pebbles and rock fragments of all sizes up to 10 inches or rarely 15 inches in diameter. Most of the pebbles and cobbles are well rounded, but some of the larger are angular, with only slight marks of water wearing. In some portions near the west end of this excavation no interbedding of coarser and finer layers of the torrential esker gravel is noticeable for 10 feet or more vertically, the spaces between the larger stones and cobbles being filled with finer gravel and sand. In the eastern half or two-thirds of the excavation, much sand and fine gravel are irregularly interbedded; and along a considerable extent toward its southeastern end a great part of the section on the southern side, near the axis of the esker, consists mainly of sand, the depth of the pit there being 50 feet.

The stratification here and throughout all the 4 miles of the esker is approximately level, with occasional slight inclination eastward, but has frequent disturbed or confused portions adjoining either side and wherever very coarse gravel abounds. Torrential oblique bedding of the finer layers is frequent, any nearly horizontal layer 1 to 2 feet or more in thickness having often a secondary "flow and plunge structure," or cross-bedding, with dips from 10 to 30 degrees or rarely steeper, almost invariably inclining downward from west to east.

Paleozoic limestones make up about 75 to 90 per cent of the gravel, the remainder being Archean granites, gneiss, and schists; and such proportions are observed through the whole course of the esker. It is thus known, by evidence of the cross-bedding and of the sources of the gravel and sand, that this esker was deposited by a glacial river flowing eastward, deriving its drift from the part of the waning ice-sheet lying on the west, where limestone formations cover large areas.

Above the esker sand and gravel along this western mile a thin envelope of true till, mostly continuous at the top of the sections both on the south and north sides of the excavation, forms a most remarkable and instructive feature, which is presently to be fully described, with ensuing discussions of its significance concerning the amount of the drift that was englacial and finally superglacial, and in its bearing on the conditions of deposition of eskers.

Within the 22 years since my former observations here, this excavation has been widened, and it has been continued about 300 feet southward from its former eastern end. Then no considerable excavation had been made along the farther course of this esker eastward; but at the present time the aggregate removed from the eastern gravel and sand pits probably exceeds the amount thus far taken from the excavation already described, adjoining Birds Hill Station. About a quarter or a third part of the whole esker has been removed. At the same rate, disregarding its prospective increase on account of the present rapid increase of building in Winnipeg, this esker will be almost completely removed during the next 40 or 50 years.

Plate 31, the frontispiece of this paper, comprises a map and sections of this prolonged ridge, and of two noteworthy kames a few miles east and southeast, called Moose Nose and Oak Hummock, which are short and nearly round hills of similar material and origin as this esker. The map also shows associated gravel plateaus, ridges, and hills on the northeast.

Through its second mile Birds Hill, or ridge, is lower, having a height of 40 to 20 feet, declining southeastward, above the adjoining level areas, from which, with their productive farms, it is distinguished, like the higher mile at the west, by narrow but mostly continuous groves of small oaks and other trees and underbrush on the lower part of either slope of the ridge, while its rounded crest is a narrow avenue of prairie grasses and flowers, of species that prefer its dry, gravelly soil. The course of this part, crossing section 33, township 11 north, range 4 east, is from northwest to southeast; and the crest was occupied, until at some places fenced across in recent years, by a road for wagons, and long ago for Indian ponies and their trailing poles. The width of the ridge along this mile, from the foot of the slope on one side to that on the other side, varies from 60 to 30 rods, decreasing southeastward.

It is excavated only along a distance of about an eighth of a mile on its southwest slope, midway between the center and southeast corner of this section 33, for transportation by a railway spur track running to the south. The section there is wholly coarse gravel, nearly level in bedding, to the depth of 10 to 15 feet thus observed. No boulders were seen in this excavation, nor along all the trail or road running on the crest of the ridge for the mile and a half thence northwest, until, near the western end of the esker, the road descends along its southwest slope to the village of Birds Hill. In that descent for an eighth of a mile the roadway and the adjoining surface are strewn with boulders, mostly granitic, up to 3 feet in diameter, which belong to the envelope of till before mentioned.

At the southeast corner of section 33 the esker sinks to the lowest and most narrow part of all its course, rising only about 8 to 12 feet above the general level on each side; and for a short distance there, some 40 rods or more, its usual accumulation of gravel and sand is replaced, or is covered, by till with plentiful boulders. Perhaps this is a place where till overlies a diminished deposit of esker gravel; but it appears to me more likely that the esker deposit ceased there for a short space. Its place is taken by the low ridge of till, gently rounded up, with a width of about 30 rods or less, imitating in general form, but on a reduced scale, the esker whose continuation it represents.

Next eastward, in the south edge of section 34, this esker is again very prominent, taking a course from west to east. It has been excavated by the Canadian Northern Railway Company on a width of 300 to 500 feet for the distance of a mile through this section, the gravel and sand being loaded on cars of spur railway tracks here running west and thence south. The road on the south line of the section rises about 50 feet above the general level, to the south edge of the top of the esker, which was somewhat flat and plateau-like for the width of 300 to 800 feet, while its southern and northern slopes add some 700 feet, making the whole width of the esker 1,000 to 1,500 feet, here having its most massive development.

The west half of this excavation consists of sand and gravel, mostly not very coarse, the pebbles in the coarser beds being from 4 to 6 inches in diameter, excavated to the depth of 10 to 20 or 25 feet, continuing still deeper on the north, but along the south line of the section seen to rest on till. In its east half the excavation is gravel and sand from 6 to 20 or 30 feet deep, underlain by till, which rises to a height of 30 to 40 feet or more above the general level, so that if the overlying esker deposit were wholly removed a broad ridge of till would be exposed.

About 800 to 1,100 feet west from the east line of this section 34, the north and lower side of the excavation showed a cut in the till 18 to 20 feet thick and 15 rods or more in length, also extending deeper. It is entirely free from evidences of water action, and contains frequent boulders 1 to 2 feet in diameter throughout its mass, not more plentiful at or near its top than below. Its whole thickness thus exposed is oxidized, having nearly the same yellowish gray color as the gravel and sand. The lack of larger boulders and their occurrence in no greater numbers at the top of the till deposit indicate that it was formed beneath moving ice, though probably thus amassed englacially, rather than by accumulation from superglacial drift, like many hillocks and ridges of marginal and interlobate moraines, which commonly are characterized by the abundance of boulders in and upon them. Coinciding in position with the broadest part of the esker, this exceptional mound or wide ridge of underlying till, rising high above the general level of the country, is almost surely attributable to conditions that produced both the prominent mass of till and the esker, in or beneath which it is a nucleal deposit.

On the north side of the west part of this Canadian Northern Railway excavation, the northern slope of the esker has been excavated along a distance of about a quarter of a mile by the Eli Sand Company, which also has large sand and gravel pits near Eli Station, some 30 miles west-northwest of Winnipeg. This cut, 10 to 25 feet deep and 10 to 15 rods wide, consists of coarse and fine gravel, with thin sand layers. The stratification, nearly horizontal, or dipping in some places 5 to 10 degrees east, is much broken by faults; and the beds are quite irregular, varying much in thickness within short distances, and having the coarse and finer layers confusedly interbedded. Cross-bedding is frequent, with the current dips inclined 5 to 25 degrees eastward. No till nor boulders are encountered.

In the southwest quarter of section 35 the esker continues east to its end, near the middle of the east line of that quarter section. At the home of Mr. Hutchings and through the west half of the quarter, it has a nearly flat top, forming a plateau about an eighth of a mile wide, 50 to 40 feet above the general level, slightly declining to the east; and the gentle slopes to the south and north make the whole width about a third of a mile. Nearly all the surface is gravel and sand, with pebbles up to 6 or 8 inches in diameter; but about 20 rods southwest of Mr. Hutchings' house several boulders are seen, 2 to 4 feet long, which may belong to a projecting part of the nucleal till accumulation.

Narrowing eastward, the esker terminates as a rounded low headland near the center of the south half of section 35, half a mile east of the Hutchings residence. In its end the Birds Hill Sand Company has a pit 20 to 30 feet deep and about 100 by 75 feet in diameter, opened about a year ago. The upper 3 to 6 feet of the rounded eastward slope at the pit are gravel, partly coarse, with many cobbles up to 6 inches or partly 8 to 12 inches in diameter, nearly all being limestone. All the excavation below is sand, or has only scanty and fine gravel. The stratification is in part steeply inclined, with dips of 20 to 40 degrees eastward, as seen in one place for a vertical extent of 8 feet, so that it seems not to be merely cross-bedding. Some contortion of the inclined beds was noticed, but no faulting. The pit goes 10 feet below the general level, finding water which is curbed as a shallow well. No till nor boulders are there, nor in the near vicinity. The sand excavated is carried to Winnipeg by a branch railway that runs eastward to the southeast corner of this section 35, and thence passes south to the Canadian Pacific Railway.

Close at the south side of the railway track, an eighth to a third of a mile east from the pit, is a beach ridge of the Glacial Lake Agassiz, consisting almost wholly of fine sand, which has also been much excavated by the Birds Hill Sand Company. The beach sand forms a ridge extending from west to east, about 10 feet thick and some 20 to 15 rods wide, narrowing eastward, brought by wave erosion from the southern flank of the esker.

Adjoining the end of the esker, a nearly flat lower plain of sand and fine gravel, 15 to 10 feet above the general level, stretches a third of a mile to the north and a half to two-thirds of a mile northeast and east. Next northeastward beyond this plain, in the central part of the northeast quarter of this section 35, is a somewhat rounded hill 20 to 40 feet high, consisting of sand and gravel on its southern slope, but of till on its top and northern slope, with many boulders up to 5 feet in diameter.

Till overlying the Esker Gravel and Sand

The most extraordinary feature of this esker is the envelope of till covering its western quarter, along the course of the great excavation first described, reaching nearly a mile east from Birds Hill Station. In the excursion of the geologists attending the British Association, this overlying till, first observed, as I think, by J. B. Tyrrell, of Toronto, Canada, was clearly seen by all the party, including several British geologists, others from Canada, and, among United States geologists, Frank Leverett and Frank B. Taylor, experts in all phases of glacial, fluvial, and lacustrine action.

Here I must make a confession and apology. That this most significant feature of Birds Hill was not observed by me in my former field work, and therefore was not described and delineated in my reports published in 1890 and 1895, was doubtless due to the thinness of the till sheet and its yellowish gray color, similar to all the esker gravel and sand.

The section and description given by me in those reports, however, especially mention a mass of till seen inclosed within the esker, of which I wrote:

> "Imbedded in this coarse gravel on the south side of the excavation I noted a mass of ordinary till, unstratified boulder-clay, inclosing gravel and boulders in a solid matrix of somewhat sandy clay, wholly bounded by definite but irregular outlines, its dimension vertically being about 10 feet and its length 20 feet. . . . It probably was derived from the drift that was contained within the ice-sheet and finally overspread its surface when the greater part of the thickness of the ice was melted. From a sheet of drift thus deposited on the ice that formed the bank of the glacial river this mass may have fallen into its channel."

No similar inclosed mass of till was seen in the sections examined last summer and autumn; but I believe that the till mass seen in 1887 and thus described was in its original position as imbedded in the esker by falling from above while the gravel ridge was being accumulated, rather than as a part of a talus fallen from the gravel and sand beds and from the overlying till sheet on account of their being undermined by the excavation.

Boulders occurring in considerable numbers over the northern slope of this part of the esker and left where the gravel and sand had been excavated, I endeavored to explain in the former reports as follows:

"Some two hundred boulders were found scattered upon the area of the excavation; and they occur with nearly the same frequency on other portions of this northern slope of the hill, but are rarely found on its top and southern slope. They vary in size from 2 to 8 or 10 feet in length; nearly all are Archean, but a few of Paleozoic limestone, up to 5 feet in length, were observed. None was seen inclosed within the gravel and sand of the esker, and the workmen informed me that they occur only on or near the surface. This hill was covered by Lake Agassiz, and its boulders were doubtless dropped or stranded from bergs and floes on this lake before the border of the ice-sheet had retreated from the vicinity. Indeed, the occurrence of the boulders chiefly on the northern slope seems to indicate that they were mostly stranded there while ice yet remained beneath this deposit and prevented its entire submergence in the lake."

Details of the esker section and the overlying till on the deeper south side of the excavation are as follows:

From its west end this section has a thin covering of till, with frequent boulders 2 to 5 feet in diameter, for a distance of about 350 feet. In the east half of this extent the till varies from 2 to 8 feet in thickness, being thickest near its east limit, where it ceases by the rising of its lower boundary at an angle of about 45 degrees to the surface. Above the till along most of this extent, excepting where it comes to the surface at the east, is a thin surface deposit of gravel 1 to 3 feet thick. The till is underlain by the very coarse water-worn esker gravel, obscurely and confusedly bedded, 10 to 20 feet thick and continuing below the excavation.

About 5 to 10 feet east from the limit of the till is a sand mass, 3 by 6 feet in dimensions, lying 2 to 6 feet below the surface, wholly inclosed in the coarse gravel, being perhaps a frozen mass there imbedded while the gravel was rapidly deposited around it.

Through the next 100 feet east the section is mostly very coarse gravel, not distinctly bedded, with pebbles and cobbles up to 8 inches in diameter, well water-worn, and also inclosing occasional partly or wholly angular rock fragments up to 18 inches in diameter, from the surface downward, seen to the depth of 20 feet. In that part, between 30 and 60 feet east of the limit of the till before noted, the gravel incloses an irregular inclined layer of sand, 6 inches to 3 feet thick, beginning at the surface and running downward to the east 12 feet in its length of 30 feet. This is the only exception to the coarse gravel otherwise making all that part of the section.

Next east for 75 feet the section, 20 to 25 feet deep, is finer gravel, with pebbles up to 4 or 6 inches in diameter, containing no unworn larger fragments; but there it is capped by a stratum, 2 to 5 feet thick, of very bouldery gravel containing subangular rock fragments up to 2 or 3 feet.

In the next 200 feet the envelope of typical till, beginning with similar abruptness as it ended, is continuous, varying in thickness from 10 to 3 feet. Three times in the distance of 200 feet it suddenly thickens downward to about 10, 7, and 8 feet respectively from west to east, and thins more gradually east from each bulge. Its top throughout is nearly level, forming the surface eastward, and overlain by a surface gravel westward, which gradually thickens to 3 feet. Under the till the lower part of the section is rather fine gravel, seen to the thickness of 20 feet, having worn pebbles up to 3 or 4 inches and no larger unworn stones. In some parts the gravel is sparingly interbedded with sand layers 6 to 18 inches thick. The stratification is continuous, though partially dim, with gentle dips of 5 to 15 degrees eastward, and displays no faulting nor disturbed bedding.

Thence a continuous layer of the same typical till, having no trace of stratification, extends about 500 or 600 feet east. It is 4 to 8 feet thick, and contains frequent rock fragments and boulders, nearly all of unworn angular forms, up to 3 feet in diameter. Except for a distance of several rods at the west, where it is the surface, the till is overlain by a surface deposit of very coarse gravel, 1 to 3 feet thick, containing rounded cobbles up to 12 and 18 inches. The till is underlain continuously by such quite fine gravel as was seen in the adjoining distance of 200 feet west, 20 to 25 feet thick in the excavation and continuing below, having pebbles from 1 to 4 inches in diameter in its various beds, but no clear sand. The stratification, often dim, nowhere faulted, is partly level, but mostly dips 5 to 10 degrees eastward.

At the east end of the part thus described, the till ends by being merged or gradually changed, within a distance of 20 to 40 feet, into coarse, well bedded gravel, which contains cobbles up to a foot or 15 inches in diameter. This deposit forms the upper 8 to 12 feet of the section for the next 300 feet east, and is underlain by fine gravel into which the excavation goes down 25 to 30 feet. Numerous layers in the lower part, 6 to 18 inches thick, are almost wholly sand. The stratification of the fine gravel and sand is nearly horizontal, or dips in some portions 5 to 8 degrees to the east; but occasionally the deposit for thicknesses of 2 to 6 feet has no definite stratification lines.

Farther east and southeast, for about a third of a mile, in the curving course of the excavation, including at its end the extensive pit lately abundantly worked by the engineering department of the city of Winnipeg, all the section on the southern and southwestern side, 40 to 50 feet deep, is good gravel and sand. Its coarser layers commonly have pebbles 3 to 5 inches in diameter, with no larger stones nor boulders and no till. Some layers are chiefly sand, with scanty gravel, and rarely a bed 1 to 2 feet thick and 50 to 75 feet long is almost clear sand.

Returning to the west end of this long excavation, near Birds Hill Station, and examining the section along its lower northern side, we have for a distance of about 2,000 feet a continuous mantle of till, 6 to 10 feet thick, mostly typical unmodified glacial drift, with frequent boulders in and upon it, but in some parts showing modification, as slight stratification and assorting by water action. The till and boulders make the surface, or through perhaps half of this distance are thinly covered by a coarse surface gravel, 1 to 3 feet thick. Beneath the till the esker gravel, excavated continuously for a thickness of 10 to 15 feet and reaching lower, has usually pebbles from 1 to 3 inches in diameter, and in some parts up to 6 inches, all water-worn, with no larger stones nor boulders. It is nearly levelly bedded, but frequently dips 5 to 10 degrees to the east.

The till terminates at the east end of the part thus noted, there being the surface and 8 feet thick, by an abrupt ascent of its lower boundary at an angle of 70 degrees with the horizon, and is succeeded by fine gravel, which immediately to the east forms all the section, exposed to a depth of 20 feet.

Within about 50 feet onward the till begins again, and it soon thickens to 6 or 8 feet, its lower boundary being inclined at first 15 to 20 degrees. When it has thus attained a depth of about 8 feet, it runs as a surface deposit 6 to 10 feet thick, or in large part is covered by 1 to 3 feet of coarse gravel, for nearly 1,000 feet. It is underlain, as westward, by fine gravel and sand, excavated to the thickness of about 15 feet, nearly levelly stratified. This stretch of the till envelope ends somewhat like the preceding, but less suddenly, tapering out from a depth of 10 feet by the ascent of its under edge to the surface at an angle of 25 degrees.

After a second interval of only 50 feet, in which the fine esker gravel comes to the surface, the coating of till is renewed and has a depth of 5 to 10 feet at the surface, or with a few feet of coarse gravel over it, as before, for the next 500 feet, curving to the southeast and south. It terminates near the end of the excavation, where in the Winnipeg City pit the whole section is again fine gravel and sand, excavated 50 feet in depth from the surface at the crest of the esker.

Formation of the Esker by a Glacial River

Independently of each other and near together in time, the origin of eskers and kames through deposition by ice-walled rivers, small or large, flowing from the melting ice-sheet, mostly in its waning stages at the end of the Glacial period, was thought out and published by D. Hummel and N. O. Holst in Sweden and Prof. N. H. Winchell and the present writer in the United States.[4]

Along the course of this gravel and sand ridge of Birds Hill a stream poured from the glacial melting and attendant rains, walled on each side by yet remaining tracts of the retreating continental ice-sheet, which gradually rose to greater heights westward and northward. The very plentiful limestone pebbles and the slight easterly dips of many portions of the esker beds demonstrate that this small river flowed southeast and east.

Wherever belts of marginal moraine hills or low hillocks and ridges are typically developed, as they have been traced and mapped continuously across more than half of our continent, from Cape Cod and Long Island to the northwestern plains of Alberta, with much interlocking and wide diversity of topographic expression and drift material, these moraines always include, within any district of much extent, considerable accumulations of stratified gravel and sand, frequently amassed separately from the marginal till and boulders, so that they form kames, that is, low mounds and knolls or sometimes prominent hills, and occasionally eskers, which are prolonged kames, associated with the other and more strictly moraine hills of till.

Birds Hill and the contiguous kames, Moose Nose and Oak Hummock, may be referred in general to glacial streams temporarily existing at some time during the stage of the receding ice-sheet when the Itasca moraine in Minnesota was heaped along its boundary; but on the area of Lake Agassiz all the moraine belts that cross it are indistinctly or quite interruptedly recognizable. These fluvial hills of gravel, with overlying and underlying till, are the most noteworthy drift accumulations that are found in the probable course of the Itasca moraine on this lacustrine area.

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[4] The early studies of Hummel and Holst, in 1874-1876, on the eskers of Sweden, where this class of drift formations has more extensive development than anywhere else in the world, are cited by Prof. James Geikie in "The Great Ice Age," second edition, 1877, pp. 414, 415.

N. H. Winchell: Geological and Natural History Survey of Minnesota, Second Annual Report, for 1873, p. 194.

Warren Upham: On the origin of kames or eskers in New Hampshire. Proceedings of the American Association for the Advancement of Science, vol. xxv, for 1876, pp. 216-225; Geology of New Hampshire, vol. iii, 1878, pp. 12-14.

Consult also the U. S. Geological Survey Monograph xxxiv, 1899, The glacial gravels of Maine and their associated deposits, by Prof. George H. Stone, treating of the region having the longest and most abundant eskers in North America.

Deposition of the overlying Till

In the sections examined on the south and north sides of the excavation near Birds Hill Station, described in the foregoing pages, the extensive but partially interrupted sheet of till above the main esker gravel deposit has only the usual proportion of boulders ordinarily belonging to the till of this region, nor are they of larger size and less worn and striated than is their usual condition elsewhere in the surrounding general drift sheet. At least two or three hundred large boulders, however, from 3 to 10 feet in length, have been found during the progress of this excavation, in and upon the overlying till.

About the west end of the esker such large and unworn boulders are more abundant, as is characteristic of marginal moraines, strewing the surface plentifully where the west foot slope of the ridge is crossed by the road leading north from Birds Hill village, and also on the southwestern slope where the road or trail descends from the crest to this village. They similarly abound again a mile farther east, on the lower part of the northeastern slope, within an eighth of a mile eastward from the deep Winnipeg gravel pit, which is the end of the excavation.

But along the crest of the esker, close above and south of the section noted at the south side of the excavation, no boulders are seen, nor on the greater part of its southward slope, the whole depth of the esker there being probably gravel and sand. Nor was any boulder observed imbedded in the sand and gravel beds in any part of the very extensive sections shown on both sides of the excavation, either at my visit in 1887 or last summer.

The best explanation, as I believe, for the mode of deposition of the till above the esker gravel is to refer it to a moderate re-advance of the front or wall of the ice-sheet from the northern side of the esker channel, carrying some of its englacial and finally superglacial drift over the northern flank and west end of the esker ridge after that part of the gravel and sand deposit had been laid down in a somewhat wide channel open above to the sky. While the till was thus being spread over the north slope and west end, the continued deposition of stratified drift by the esker stream may have been adding to the thickness of its axial portion, raising its crestline above the till-covered northern slope.

In the halting and partly readvancing and wavering stage of the ice-border when any marginal moraine was accumulated, many of its kames were probably more or less covered with till and boulders; but the occurrence of a till envelope or mantle upon an esker is very rare. The observations here recorded for Birds Hill are perhaps the most remarkable in this respect that have been made known in the extensive literature of glacial geology.

Apparently a readvance of the ice-front from the north and west to an extent of about 1,000 feet beyond its former place, along this distance of about 1 mile, satisfactorily accounts for these sections of till above the esker gravel and sand. Such oscillation of the ice-wall required possibly only two or three summers, but more likely the summers of a decade, more or less, averaging a little cooler than the preceding and following years of relatively rapid wane and withdrawal of the ice-fields at the end of the Glacial period. The thin gravel beds at the surface above much of the till sheet may have been formed a few years later, when the previously onflowing border of the ice was melting away.

In passing we may add that the whole duration of Lake Agassiz in this basin of the Red River and Lake Winnipeg, with retreat of the ice boundary across the 1,000 miles from western Minnesota to Hudson Bay, appears to have measured only about a thousand years, as estimated from the amount of its wave erosion and beach sand accumulation, in comparison with the much greater amount of similar work done by Lake Michigan and others of the Great Lakes of the Saint Lawrence Basin since the Ice Age. As a very small part of that time of duration of the glacial lake and departure of the ice-sheet from its area, we may reasonably infer that the time occupied in the accumulation of the kames and esker near Winnipeg must have been short, probably not exceeding 20 or 30 years.

Depth of the Esker shown by Wells

To provide water for the workmen in the excavation, a well 45 feet deep had been dug or bored at its bottom about a half mile from Birds Hill Station before my visit in 1887. It was wholly in the same formation of gravel and sand, showing for this deposit there a thickness of about 90 feet below the crest of the esker, or some 40 or 50 feet below the general level of the flat valley plain.

Again, about a third of a mile farther east a second well, recently dug or bored for the workmen of the Winnipeg pit, goes down below that pit 40 feet in the same stratified drift to water. Like the preceding well, it gives a depth of 90 feet for the esker deposit. The important and very significant feature thus proved is that the fluvial gravel and sand continue about 40 feet lower than the level of the surrounding country. As will be more fully explained on later pages, this implies that a very large part of the general drift-sheet was material contained in the ice-sheet, borne along by it above the subglacial land.

Neil J. McGregor's well in Birds Hill village, about 15 rods southwest from the edge of the esker ridge near its west end, bored last summer, has this section: Soil, 1 foot; bluish till, with few boulders, 11 feet; gray till, 8 feet; coarse gravel, all water-worn, with nearly all the cobbles limestone, very abundant, 1 to 10 inches in diameter, 40 feet; less coarse gravel, or more probably till, with only few stones, 10 feet; limestone, the bedrock, 28 feet, to the bottom of this well, at 98 feet, whence water rises in the well pipe 70 feet, to 20 feet below the surface.

Here we may think that an englacial tunnel, occupied by a torrent that had fallen through crevasses and moulins of the ice, thence flowing through this tunnel to join the esker river, became filled with the torrential gravel, similar to that chiefly forming the west end of the esker. The bottom of the coarse gravel in this well is at a depth of 60 feet from the surface, being somewhat lower than the bottom of the wells in the excavation. The bluish gray color of the till, extending to the surface, is due to its relatively unoxidized and unleached condition, in contrast with the yellowish gray till of the esker, where its height above the adjoining land has permitted infiltration of the water of rains, favoring the change of its iron element from the protoxide combinations to the rust-coloring sesquioxide. The same bluish gray till forming the surface is seen at the post-office kept by George Chudleigh, at the school-house, and indeed in all the cellars and wells of the village.

Relationship to the Glacial Lake Agassiz

If the overlying till in Mr. McGregor's well, having a thickness of 20 feet, represents an average of the amount of englacial till above the level in the ice-sheet at which the esker was formed, the total quantity of englacial drift was apparently equal to a thickness of 30 feet or more, some two-thirds of it being held and carried along higher in the ice than the highest level of Lake Agassiz here, which was about 500 feet above the present land surface.

Much of the interest of this subject depends on the relation of Birds Hill to Lake Agassiz. The esker is situated near the center of the area of the ancient glacial lake. On the east border of its area the Herman Beach, the earliest and highest of a series marking the boundaries of the old lake, is mapped from the southward outlet at Browns Valley, Minnesota, in its course north and northeast to the vicinity of Red Lake, being there 1,210 to 1,215 feet above the sea; and on the west it extends through North Dakota and onward across the Assiniboine River to Riding Mountain, west of the south part of Lake Manitoba, there lying at an altitude of 1,300 to 1,320 feet above the sea.

It is thus evident that when the ice-sheet had so far receded that its border was being melted away in the vicinity of Birds Hill, permitting the esker to be formed by a stream flowing from it, the level of the ice-dammed lake there, about midway between Red Lake and Riding Mountain, was about 1,260 feet above the sealevel. Comparing that height with the surface at Winnipeg, 757 feet, at Birds Hill Station, 759 feet, and the level of Lake Winnipeg, 710 feet, we see that the ancient Lake Agassiz was 500 feet deep above the site of Birds Hill at the time of formation of this esker, the lake then being at its earliest and highest stage.

Further, it seems to me quite surely demonstrated by the described characters of the stratified drift forming this esker of Birds Hill, that its deposition took place from a freely running stream in a channel that was inclosed on the sides by walls of the waning ice-sheet and was open above to the sky. It was not deposited in the still water of a deep lake, between channel walls of ice rising from the land surface; for then the esker gravel and sand and the frontal lower plain adjoining the east end of the esker could not have been spread out as they now are found. Fluvial currents, such as could only exist above the surface of the adjoining Lake Agassiz, brought and laid down the modified drift of the ridge and its terminal plain. Afterward, by the completion of the melting and retreat of the ice-border here, on each side and beneath the esker and plain deposits, they were allowed to sink gradually about 500 feet, until they rested on the land.

A short summary of the history of Lake Agassiz needs to be added. Beginning as a small lake at the southern end of the wide Red River valley outflowing to the south in a channel where Lakes Traverse and Big Stone now are, it grew in length northward with the recession of the ice-sheet which was its barrier. Beyond the limits of my explorations of its shorelines, passing through Minnesota, North Dakota, and southern Manitoba, north to the Riding Mountain, its farther extent northward, by Riding and Duck mountains and the Porcupine and Pasquia Hills and across the Saskatchewan River, has been explored by J. B. Tyrrell for the Canadian Geological Survey. Its length grew to at least 700 miles, and its area doubtless exceeded 100,000 square miles, surpassing the combined areas of the Great Lakes tributary to the Saint Lawrence.

After the formation of the uppermost or Herman beach, a series of several lower beaches with outflow still to the south was formed by the downward erosion of the channel of the outflowing river. Still later a large series of yet lower beaches recorded the successive lower outlets of the lake while it outflowed northeasterly, previous to the full melting of the central part of the ice-sheet. Finally the area crossed by the Nelson River and the basin of Hudson Bay were uncovered, allowing the glacial lake to be wholly drained away, excepting its present representatives, Lakes Winnipeg, Manitoba, and Winnipegosis, lying in hollows of the land.

Meanwhile, through the greater part of the time of existence of Lake Agassiz, this part of the earth crust, unburdened by the melting of the thick and heavy ice-sheet, was gradually rising, and its greatest uplifting took place in the central part of the formerly ice-covered area. Thus the successive early shorelines of Lake Agassiz were much uplifted, with all the lake basin, most in the central region of the continental glaciation, and least about its boundaries. This continental uplift gave to the highest and oldest shore a northward ascent that averages nearly a foot per mile for 400 miles from the southern mouth of the glacial lake. Its lower and later shores are each less inclined than the preceding, until the lowest beach is scarcely changed from its original horizontality, showing that the great uplift of this lacustrine area was practically completed before the ice-barrier on the lower part of the course of the Nelson River disappeared.

A part of a very sandy beach ridge of Lake Agassiz adjoining the east end of this esker has been much excavated for the use of its sand by the Birds Hill Sand Company, as before noted.

Again, about a mile and a half west from that place a more typical but smaller beach ridge is crossed by the roads on the north and east lines of section 28, township 11 north, range 4 east, about 2 miles southeast of Birds Hill Station. This beach, running from northwest to southeast, crossed by each road about 20 rods from the northeast corner of this section, is excavated to depths of 3 to 5 feet at the roadside, and is seen to be fine gravel and sand. Much of the beach deposit consists almost wholly of pebbles from 1 to 3 inches in diameter. It is a very low, gently rounded ridge, about 4 to 6 rods wide, elevated at its crest only 3 or 4 feet above the land adjoining its northern side, which is close to the depressed and till-covered part of the esker's course. The southwestern and lakeward side of the beach ridge has a descent of some 5 or 6 feet in 3 or 4 rods, to the edge of the very slowly declining flat lowland of till next south, where the lake at the time of its accumulation of the beach had a depth of 2 to 5 feet.

Both of these beach deposits, observed only for short distances, probably belong to the lowest or Niverville stages of Lake Agassiz, represented near Niverville, Otterburne, and Morris, south of Winnipeg, by small beach ridges, 2 to 4 feet high, whose crests vary from 777 to 784 feet above the sea. Exact leveling from Birds Hill Station seems desirable to ascertain the heights of these shorelines. Until this test shall be applied, I think the eastern sandy beach to be at or near 780 to 785 feet, and the western and less conspicuous beach probably several feet lower.

Other Esker and Kame Deposits in the Vicinity

Township 12 north, range 5 east, from 4 to 12 miles east and northeast of Birds Hill Station, has numerous esker ridges, shorter hills, and extended plateaus of gravel and sand, from 50 to 100 feet above intervening swamps, parts of which are well wooded with spruce and tamarack. The uplands, forming plateaus, eskers, and kames, are largely prairie, but in some tracts are scantily wooded with scrubby oaks, elsewhere with a better growth of poplars, and eastward have a few white pines.

One of the most conspicuous of these elevations, as viewed from the west, is called Griffiths Hill, on the township plat in the Dominion Lands Office at Winnipeg, drafted in 1872 from the original surveys. The top of this hill, in the northeast quarter of section 19, is about 875 feet above the sea, or a little more than 100 feet above the railway, 2 miles distant on the west.

The whole group is composed of gravel and sand, and the topographic forms indicate deposition by glacial rivers near their mouths, where they flowed between walls of ice, being here and there divided by ice-islands, whose melting left the hills, ridges, and plateaus bounded by moderately steep slopes. With the completion of the melting of the ice about and beneath these deposits, they sank to the bottom of Lake Agassiz. Toward the north, west, and southwest they border on the flat plain of the Red River valley, 750 to 760 feet above the sea, while toward the east and southeast they are connected with plains and undulating tracts of gravel and sand which extend with slow and gradual ascent to the Lake of the Woods and into Minnesota.

About 2½ miles east from the east end of the esker of Birds Hill is the Moose Nose, a conspicuous rounded hill, mainly composed, so far as can be seen on the surface, of modified drift—that is, the gravel and sand brought and deposited by a glacial river. This massive kame covers an area about two-thirds of a mile in diameter, in the west part of section 29 and the east half of section 30, township 11 north, range 5 east. The kame deposit surmounts a larger somewhat elevated oval area of typical till, which comprises most of the eastern two-thirds of section 30 and continues south in the north half of the northeast quarter of section 19, rising by very gentle slopes to the height of 25 to 40 feet above the general level of the flat surrounding country. With steeper slopes the kame rises to a flat or moderately undulating top, which may be called a plateau, 70 to 80 feet above the same level, having an area of 50 acres or more.

In addition to its basal tract, till may also form a nucleus of the higher kame; for beside the road on the line between sections 29 and 30 an excavation 5 to 6 feet deep, near the top of the southern slope, is in part true till, which is seen to a thickness of 4 feet and continues lower. Thence for an eighth of a mile north, on the highest part of the road, and for 500 feet or more east and west from the road, granitic boulders up to 5 or 6 feet in diameter are frequent in and on the sand and gravel that form the surface, probably belonging to an underlying till very thinly veneered with modified drift.

Sunnyside Cemetery, on the highest eastern part of this kame plateau, has an extensive view for several miles eastward and southward; but toward the west a far view is prevented by the low oak woods with which the kame is covered, except clearings of a few acres designed for cultivation but abandoned because of their gravelly and sandy soil.

On its east border the kame deposit of the Moose Nose has been extensively excavated for ballasting the Canadian Pacific Railway, being removed by a branch line running south. The whole excavation, a quarter of a mile long, from 10 to 200 feet wide, and exposing a section 25 to 40 feet deep, consists of gravel and sand, which continue lower, with no till nor even a single boulder. About a fourth part is clear sand, in layers up to 2 feet thick; the other three-fourths are gravel, varying in coarseness to occasional layers holding cobbles up to 8 or 12 inches in diameter, or quite rare up to 18 inches, all well water-worn. Nearly all the pebbles and cobbles are limestone. The stratification is horizontal, with infrequent cross-bedding, which, wherever observed, dips a few degrees to the east. All the section is very definitely stratified, and it has no fault lines nor places of confused or obscured layers.

Oak Hummock, in the southeast part of section 12, township 11 north, range 4 east, also extending a third of a mile east into section 7 of the next township, lying thus 3 miles south of the Moose Nose, has nearly as great area but less height, rising only 45 to 50 feet above the surrounding level. It has an oval outline a mile long from west to east and two-thirds of a mile wide. This hill consists mainly of kame gravel and sand, but has an underlying rounded accumulation of till, which rises to a height of about 30 feet, or two-thirds as high as the kame deposit.

A shallow but long cut across the northern side of this hill has been made on the course of the electric power line that brings power from Lac du Bonnet to Winnipeg, passing from east to west through the center of these sections 7 and 12. The cut, made to supply ballast to the Canadian Northern Railway by a track running west, is a half mile long, extending through the east half of section 12, and is only 5 to 8 feet deep; but as the railway grade rises some 25 feet above the general level, the top of the cut is at the height of 30 feet or more. The west half of the cut is very coarse gravel, nine-tenths of it consisting of pebbles and cobbles from a half inch to 8 inches in diameter, of which fully 95 per cent are limestone, the others being mostly granitic. The formerly steep sides of the excavation had mostly fallen down at the time of my visit last September, so that the stratification was visible only for a small part, there showing dips of 5 to 30 degrees east.

The underlying till rises with a very gentle and smooth slope beneath the east part of the gravel, and forms the surface onward for about an eighth of a mile, along the eastern quarter of the cut, or is in part overlain by a surface stratum of the coarse gravel 1 to 2 feet thick. It contains plentiful rock fragments and boulders, up to 3 feet in diameter, most of the large boulders being granitic, while nine-tenths or more of the small fragments are limestone. As in the Moose Nose and Birds Hill, the stratification of the gravel and the material of both the gravel and till denote derivation from the west.

On the township line road crossing this Oak Hummock from north to south, the surface is till from the east end of the cut for some 30 or 40 rods south; but the higher part of the hill, rounded and somewhat irregularly rolling in contour, consists of gravel and sand, without boulders. It is mostly wooded with poplars, scrub oaks, and bushes; but it has two small cleared fields which were formerly cultivated. An excavation near the southeast corner of the northern field, about 100 feet in diameter and 6 to 10 feet deep, is all coarse gravel, nearly as in the railway cut.

How confluent currents of the ice-sheet heaped the till in its prominent underlying and nucleal accumulations which form parts of Oak Hummock, the Moose Nose, and the east half of Birds Hill will here receive no attempt for explanation, other than to indicate that the glacial movements thus amassing the till were closely related with the contour of the ice surface which immediately afterward caused an ice-walled river to bring and deposit in these places the sand and gravel of the kames and esker. Further study may be profitably given for ascertaining the conditions of drift transportation and deposition by which these till accumulations were formed, and they may contribute light on the difficult question of the origin of drumlins.

In the general northward recession of the glacial boundary, its strong frontal currents of the ice heaping a part of its till, and closely succeeding exceptionally large fluvial deposits, formed earliest the Oak Hummock, next the Moose Nose, and latest Birds Hill, though probably no long intervals divided the times of their formation.

Where the boundary of the ice-sheet lay eastward of Birds Hill at the time of its slight readvance which spread till and many boulders over the western part of that esker is perhaps indicated by the abundance of boulders on the surface of the till forming the top and north slope of the low hill in the northeast quarter of section 35, township 11 north, range 4 east, before described in connection with the east end of the esker, which is three-fourths of a mile distant to the southwest, in the southern part of the same section. A half to three-fourths of a mile farther northeast, in the south part of section 1, township 12 north, on the cleared course to be occupied by a new line of transmission of electric power, very abundant boulders are similarly found on the northwestern end of a wooded ridge, 50 to 75 feet high. Eastward this ridge is probably an esker, and after an extent of about a half mile to the southeast and east it widens into a prairie plateau or plain, composed of modified drift, reaching northeast and east 2 to 3 miles or more, and having a height 75 to 100 feet above the extensive level lowland on the south.

Nearly all the plateau has a surface of gravel and sand, but about 2 miles east-northeast from the very plentiful boulders noted in section 1, a tract of several acres, distinguished from the general prairie by its scattered small oaks, has many boulders up to 6 feet in diameter, both of granite and limestone. The surface there on a small area thus appears to be marginal till, though not differing much in height or contour from other parts of the general plain of modified drift. This place is close east of the most western of several lone white pines, the first seen in going eastward from the Red River valley.

Connecting these places of unusual profusion of boulders, we have a course of about 7 miles marked interruptedly by one of the most characteristic features of marginal morainic drift. Therefore we may perhaps rightly picture in our minds a steep frontal ice slope or cliff extending along that distance from the site of Birds Hill Station to the lone pine and scrub oaks, readvancing a few hundred feet and depositing its boulders so plentifully in these several places.

Belt of modified Drift extending Southeastward

Modified drift, consisting of stratified gravel and sand, with local deposits of clay, overlies the bedrocks and the till, and generally forms the surface, on an extensive area stretching from the vicinity of Birds Hill southeasterly to the southwest part of the Lake of the Woods and to the Rainy River, and continues on large tracts in Minnesota, to the lakes at the sources of the Mississippi and to the Leaf Hills, and thence southeastward to Minneapolis and Saint Paul. The contour of the greater part of these deposits, through their extent of 400 miles, is flat or moderately undulating, and their surface varies in height from a few feet to 50 feet or rarely more above the adjoining lakes and streams. In central Minnesota these tracts of gravel and sand have an elevation that increases from south to north, being 825 to 950 feet above sealevel in the vicinity of Minneapolis and Saint Paul, rising gradually to 1,200 feet in the distance of about 100 miles northwest to Brainerd, and ranging from 1,350 to 1,500 feet between the Leaf Hills and Itasca Lake. Thence their surface sinks to 1,150 and 1,075 feet in the vicinity of Rainy River and the Lake of the Woods, and is between 750 and 875 feet in the district here especially described, northeast of Winnipeg.

On each side this broad belt is bordered by areas of nearly the same general elevation, which have mostly a surface of till; and it is to be remarked that the heights of the tracts of modified drift and till are alike determined by that of the underlying rocks on which these superficial deposits are spread as a sheet of slight depth in comparison with the gradual change in their elevation. The drift-sheet on this belt, including both the sand and gravel and the underlying deposits of till, probably varies in its average thickness from 50 to 150 feet, while its central portion rises 400 to 600 feet above its south and north ends.

The distribution of the modified drift thus found on large tracts along a wide belt from Saint Paul to Winnipeg, while it is very scantily developed on a still wider region of Minnesota, North Dakota, and Manitoba southwest of this belt, and likewise is scanty or wanting on its northeast side in northern Minnesota and about Rainy Lake and the northeast and north portions of the Lake of the Woods, seems to be attributable to converging slopes of the surface of the ice-sheet and the consequent convergence of its currents, which brought an unusual amount of englacial drift into the ice along this belt, and by which also the streams produced in its melting were caused to flow thither from extensive tracts of the ice on the east and west. The glacial striæ of these adjoining areas show that on the east the course of the motion and the descent of the surface of the ice-sheet were from northeast to southwest, but that on the west the glacial currents moved and the ice surface sloped toward the southeast.

Drift limestone is absent or very rare on the east, because no limestone formations were crossed within several hundred miles by that part of the ice-sheet; but on the west the drift, consisting chiefly of a thick sheet of till, contains much fine limestone detritus, sand and gravel, and frequent boulders of limestone, borne southeastward from Manitoba over the Archean area of the southwest part of the Lake of the Woods, of Rainy River, and of northern and central Minnesota. In the same directions with the slopes of the ice surface, which are known from the courses of the glacial striæ and the transportation of the drift, the streams of the glacial melting flowed convergently from the east and west, from the ice over northern Minnesota and eastern Manitoba on one side, and from that over the Red River valley and western Manitoba on the other, toward this belt of plentiful superficial deposits of gravel and sand.

Evidence of much englacial and superglacial Drift

The chief reason for the detailed descriptions presented in the foregoing pages is my wish to have other field workers and theorists in glacial geology come to my point of view and conclusions, that a great amount of drift was contained in the lower part of the ice-sheet, was carried along with its motion, and during the final melting became superglacial when the upper part of the ice melted away. The esker deposit of Birds Hill is shown by the wells in and near it to extend 50 or 60 feet below the general level of the Red River Valley plain, to a depth only 10 feet above the limestone bedrock. Seeing that the esker gravel and sand were originally deposited, as before shown, at or above the level of Lake Agassiz, which in its earliest and highest stage here, at the time of this esker river, was 500 feet above the land surface, I must conclude that the englacial and later superglacial drift of the ice-sheet here above that level amounted to about 20 feet, the thickness of the till above the coarse gravel in Mr. McGregor's well.

Beneath the level of the glacial lake, in the lower 500 feet of the ice-sheet, the quantity of englacial drift seems to have given a thickness of 10 feet, if we thus consider the entire drift deposit beneath the coarse gravel in this well, attributing none of it to subglacial deposition.

As the surface at the well is 6 or 8 feet above the general level of the adjoining valley plain, its depth of 70 feet to the bedrock indicates that the general sheet of the drift and lacustrine and alluvial beds together averages 60 feet in thickness in this vicinity. From my observations of till at or near the surface of the valley plain in many tracts about Birds Hill and Winnipeg, and elsewhere along all the length of the Red River valley, the amount of lacustrine sedimentation appears to have been slight and even negligible, excepting on areas of deltas where the lake received tributary streams laden with modified drift. Most of the stratified clay and silt along the axial lowest part of the valley, as about Birds Hill, seems therefore referable to alluvial deposition by river floods after the glacial lake had been drained away. Both lake sediments and river alluvium are absent from the tracts of till, indicating there for the till alone a probable thickness of 50 or 60 feet. On other areas, where the alluvium is deep, as generally along the central part of the valley, quite probably the underlying till averages likewise some 50 feet in thickness, nearly all of which, according to the evidence afforded by Birds Hill, was englacial and finally superglacial.

The distance from Birds Hill to the boundary of the glacial drift is about 700 miles to the south and 300 miles to the southwest. It may be estimated, from altitudes of the drift on the White Mountains, the Catskills, and the Adirondacks, that the ice-sheet similarly rising over Manitoba attained a maximum thickness of at least one mile, or more probably one and a half miles, about 8,000 feet. The gradients of its surface were similar to the slowly ascending slopes by which the ice-sheets of Greenland and the Antarctic Continent rise to altitudes of about 2 miles above the sea. In the lower quarter or sixth part of the ice covering Manitoba—that is, to a height of probably 1,500 feet—much drift had been carried by its variable and partly rising currents.

Near the border of the ice-sheet during its time of accumulation, little drift could thus be carried into it, and therefore in the melting and recession of that outer part the englacial drift was generally inconspicuous; but at any considerable distance within the glaciated area, as a score of miles or more, the final melting set free much formerly englacial till and modified drift. Failure to recognize the origin of these deposits in New England has led a recent investigator of its glacial history to add, erroneously, as the present writer thinks, a late and distinct stage of glaciation to account for what seems to me an envelope or mantle of englacial drift spread over that region.[5]

The processes of drift transportation and deposition here emphasized were well stated by Prof. N. H. Winchell in 1873,[6] by Prof. C. H. Hitchcock in 1878,[7] and by me in 1876 and 1878 and in numerous later

[5] Frederick G. Clapp: Complexity of the Glacial Period in northeastern New England. Bull. Geol. Soc. Am., vol. 18, pp. 505-556, with plates 57-60, February 20, 1908.

[6] The drift deposits of the northwest. Popular Science Monthly, vol. iii, pp. 202-210, 286-297 (especially page 294, relating to superglacial drift).

[7] Geology of New Hampshire, vol. iii, pp. 282, 283, 309, 326, 333-338.

papers.[8] At the present day these processes are exemplified by the Malaspina Glacier or piedmont ice-sheet in Alaska, which during the last century has been much reduced in area and thickness; but the Greenland and Antarctic ice-sheets, which are now constant or increasing by snowfall, have no superglacial drift.

Conditions of the Origin of Eskers and Kames

In my first paper on this question, before cited, written 33 years ago and based on my studies in New Hampshire, the rivers forming eskers were thought to be mostly subglacial, although in many instances they were supposed to flow in "deep channels along lines of depression upon the surface of the glacier." The latter explanation, however, soon appeared to me preferable for all the eskers that then and subsequently I have examined, while quite short ridges and knolls or hills of the same gravel and sand, called kames, are ascribed to sudden and brief deposition by such ice-walled rivers close to their mouths.[9]

Believing that the ice-sheet nearly everywhere contained much englacial drift, I deem the absence or very rare occurrence of boulders in the gravel and sand of eskers and kames to be a conclusive argument against their subglacial deposition. Nowhere except on the western part of Birds Hill have I found or learned of an esker enveloped with till, as would apparently be common if these gravel ridges were formed beneath the border of the departing ice-sheet. Because only the west end and north

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[8] Proceedings of the American Association for the Advancement of Science, vol. xxv, for 1876, p. 218; vol. xxviii, for 1878, pp. 299-310.

Geology of New Hampshire, vol. iii, 1878, pp. 9, 10, 175-176, 285-309.

Final Report of the Geological and Natural History Survey of Minnesota, vol. i, 1884, pp. 440, 603-604; vol. ii, 1888, pp. 252, 254-256, 409-417.

Bull. Geol. Soc. Am., vol. 3, 1892, pp. 134-148; vol. 4, 1893, pp. 191-204; vol. 5, 1894, pp. 71-86; vol. 6, 1895, pp. 343-352; vol. 7, 1896, pp. 17-30; vol. 8, 1897, pp. 183-196.

American Geologist, vol. x, 1892, pp. 339-362; vol. xii, 1893, pp. 36-43; vol. xiv, 1894, pp. 69-83; vol. xvi, 1895, pp. 100-113; vol. xix, 1897, pp. 411-417; vol. xx, 1897, pp. 383-387; vol. xxiii, 1899, pp. 369-374; vol. xxv, 1900, pp. 273-299.

Proceedings of the Boston Society of Natural History, vol. xxvi, 1893, pp. 2-17.

[9] Geology of New Hampshire, vol. iii, 1878, pp. 12-14, 43-48, 62, 71, 76, 84-93, 99, 106-108, 115, 117, 127, 137-138, 144, 147, 155, 162, 167-170, 174-176.

Final Report, Geological and Natural History Survey of Minnesota, vol. i, 1884, pp. 444, 582, 624; vol. ii, 1888, pp. 168, 185, 234, 486, 490, 550.

Proceedings of the American Association for the Advancement of Science, vol. xxviii, for 1879, pp. 303-304.

Proceedings of the Rochester, New York, Academy of Science, vol. ii, 1893, pp. 181-200.

Bull. Geol. Soc. Am., vol. 12, 1894, pp. 71-86.

American Geologist, vol. xiv, 1894, pp. 403-405.

U. S. Geological Survey Monograph xxv, The Glacial Lake Agassiz, 1895, pp. 157, 179, 182-188, 210.

slope of Birds Hill, for about a mile, are covered with till and boulders, while they are absent from the top and south slope, they seem impossible to be ascribed to an unmelted arch of the ice-margin inclosing the glacial river in a tunnel, but to be due to a slight readvance of the ice-front from the north side of the glacial river.

The conclusion that there was much englacial drift, which became exposed at last on the thinned ice-margin, carries with it the consequent reference of eskers and kames not to subglacial but to superglacial drainage. Melting of the ice-sheet near its receding boundary at the end of the Glacial period was probably far more rapid than is known anywhere on glaciers and ice-sheets of the present time; so that any crevasses or moulins would speedily be obstructed by drift carried into them, causing the rivers from the ice melting and rains to flow down on the surface of the ice to its margin.

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RELATIONSHIP OF NIAGARA RIVER TO THE GLACIAL PERIOD[1]

BY J. W. SPENCER

(Read before the Society December 29, 1909)

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PREFACE

In my investigations leading to "The Evolution of the Falls of Niagara" the most important problems were those bearing on the changing physics of the great cataract. To a relatively small extent the valleys buried beneath the drift produced effects, but that which was written on the features of the drift was only preliminary and should not be considered as a complete investigation of the subject, as lack of time did not permit of a full treatment. The river was regarded in a general way as postglacial for that region only. With those notes now amplified by more complete details and the features still impressed on my mind, a better description can be given of the changing Pleistocene formations in this locality than that previously published.

STUDIES OF THE WHIRLPOOL-SAINT DAVIDS VALLEY

The peculiarities of the Whirlpool were first described by Lyell in 1841. He thought the Niagara River formerly passed by this now buried

[1] Manuscript received by the Secretary of the Geological Society January 15, 1910.

channel to the edge of the Niagara escarpment, 2½ miles northwest of the Whirlpool. During the next 40 years it seems this view was not questioned. However, in 1881, I showed there was a lower preglacial depression from Lake Erie than that over the rocks of Niagara Falls, and accordingly the Whirlpool-Saint Davids Valley could not have been the former outlet of the Erie basin, and that Niagara is a modern river throughout.[2] This was the revival of the study of the science of Niagara, but it is now known that there are at least three lower depressions across the belt of Niagara limestones than at the falls—all of which lie beneath the drift—and that the main buried outlet of the Erie basin is from 12 to 14 miles west of Niagara.[3] At one time I conjectured that the Whirlpool-Saint Davids Valley was preglacial. Then Dr. Julius Pohlman and Prof. E. W. Claypole[4] wrote on this buried valley. Later I modified my hypothesis and considered the buried channel as preglacial,[5] which view I have since maintained. However, as late as 1901, Dr. G. K. Gilbert thought that the gorge had been developed back to the Whirlpool during interglacial days.[6] Let us see what light is thrown on the subject.

Features of the Whirlpool-Saint Davids Gorge

The head of this buried canyon, for such it is, occurs at the south end of the Whirlpool, some 3 miles from the edge of the escarpment. Above this point is a smaller and shallower channel heading in the rocky divide 2 miles farther south. Beyond this ridge is another ancient valley, trending in the southward direction and deepening to 66 feet in a mile and a half, at the site of the falls themselves. In this distance the buried valley broadens from less than a quarter of a mile to over a mile, and gradually descends a more gentle gradient throughout a longer course than that of the Whirlpool-Saint Davids Gorge. This course is by way of the Falls-Chippawa and Erigan valleys, as described in "Evolution of the Falls of Niagara."

[2] Proceedings of the American Philosophical Society, vol. xix, 1882, pp. 300-337 (read March 18, 1881). It was due to the inspiration of Prof. J. P. Lesley that all my subsequent investigations of the physical history of the Great Lakes, Niagara, and, indeed, of the submarine valleys, were made. He was the father of the science of topography and of its offspring, geomorphology.

[3] J. W. Spencer: Falls of Niagara; their evolution and varying relations to the Great Lakes; characteristics of the power and effects of its diversion. Geological Survey of Canada, 1907, pp. xxxi, 490, map, 46 plates, 30 figures.

[4] Pohlman: Proceedings of the American Association for the Advancement of Science, 1883-1887, and Transactions of the American Institute of Mining Engineers, 1889, and Claypole in Science, 1886, p. 236.

[5] American Naturalist, 1887, pp. 269-271.

[6] Gilbert: Map of Niagara River, 1901.

The buried gorge leading from the Whirlpool is bounded by compact limestones with their faces steep, except where these are rounded and glaciated, with striations along the direction of its course. In breadth the ancient and now buried gorge increases from 1,400 feet at the Whirlpool to 1,800 feet in a distance of 2½ miles. Having discovered in this gorge, at a depth of 186 feet, the remains of a buried interglacial forest, its glacial history is the theme of this paper.

As shown by Professor Coleman, the first announcement of the occurrence of interglacial beds in Canada was made by my friend, the late Mr. D. F. H. Wilkins. The locality was at Port Rowan, on the shores of Lake Erie.[7] This was in 1878. A little later the original work at Scarboro Heights, just east of Toronto, was published by Dr. George Jennings Hinde.[8] This was the foundation of interglacial geology in the Ontario basin. The locality has since been studied by many, especially by Prof. A. P. Coleman, Prof. D. P. Penhallow, Dr. William H. Dall, Mr. Simpson, and Mr. S. H. Scudder, who have examined the structure and the plants, shells, and insects. These drift deposits fill and are banked up over the trough of the preglacial outlet of Georgian Bay, discovered by the writer in 1888. The drift filling the Whirlpool-Saint Davids Valley can now be brought into comparison with the drift deposits on the northern side of the lake.

Pleistocene Deposits of Whirlpool-Saint Davids Gorge

In the neighborhood of the gorge the surface of the Niagara limestone floor has been planed off, polished, and grooved, the strongest striations being in the direction of south 60 degrees west, and weaker ones south 60 degrees east, and also south. These are best seen at the quarry on the mountain top east of Saint Davids, where the drift is reduced in places to only 4 feet. While the drift over the buried valley rises higher on the edge of the escarpment, its surface at the well to be described is 340 feet above Lake Ontario. The boring reached to a depth of 268.5 feet, or to 71.5 feet above the lake—that is, within 25 feet of the surface of the Whirlpool; but the buried channel may occur to 100 feet or more below the bottom of the well. After passing the upper 40 feet of clay, the materials could hold no water until reaching the level, 33 feet above the Whirlpool. The section obtained was as follows:

[7] Canadian Naturalist, vol. viii, 1878, pp. 82-86.

[8] Canadian Journal, Toronto, vol. xv, new series, 1878, pp. 388-413.

Section of Drift in the Whirlpool-Saint Davids Canyon

	To depth of—	Height of base above Lake Ontario.
	Feet.	Feet.
Surface of ground	0	340
I. Till.—Reddish clay with few pebbles and glaciated stones[9]	40	300
II. Interglacial.—Rounded gravel, 2 feet, over light brownish, fine, sandy loam, which is also calcareous, 38 feet	80	260
III. Till.—Small angular to rounded gravel, mostly quartzitic, in red clay matrix, 4 feet; loam with gravel as above, 10 feet; angular gravel with little clay binding, 26 feet	120	220
IV. Interglacial and glacial (?).—Bluish clayey sand with angular fragments. (Boring here was rapid, with admixture of recovered materials)	186	154
V. Interglacial land surface.—Six inches of fine white sandy soil deoxidized, with twigs and a well preserved trunk of northern white spruce. It rests on a grayish clayey sand, which when the calcareous and ferruginous matter are removed is similar to the deoxidized soil above. This also contains twigs of wood	220	120
VI. Till.—Angular and subangular gravel, mostly quartzitic, size of peas, with some earthy binding materials in variable layers. At 6 feet below the top was brown rusty sand (indicating an interglacial surface), strongly magnetic. At 15 feet the fragments were large. Subangular at base	243	97
VII. Interglacial (?).—Loamy sand with quartzitic pebbles, which at base are rounded	259	81
VIII. Interglacial.—Very fine siliceous flour, somewhat calcareous, but very rich in magnetic sand. Deposit held water, flowed upward in casing for 8 feet, like cement, and stopped the boring	68.5	71.5
IX. Interglacial (?) or glacial (?) to more than	293	47

(This is the level of the whirlpool, but the drift may continue for 50 or 100 feet less or more.)

At well number 2, near by, the upper red clay passes into blue clay; and below is the loamy sand, which is well developed at well number 4 on my map. The upper layer holds water, but in the deep well no water was retained between the upper clay number I and series number VIII. At a locality 3 miles above the mouth of Niagara River, and extending below the level of Lake Ontario, occurs a blue clay in an ancient depression

[9] See Evolution of the Falls of Niagara, p. 133.

which has not been correlated with the deposits that were sheltered in the ancient canyon, but the topography in both shows eroded valleys, excavated out of the Medina shales of very much greater size than any later ones of interglacial or postglacial date.

Neighboring Drift Deposits

The surface clay rests on the polished rock northwest of the falls, and refills the now buried Falls-Chippawa Valley. Here beneath the surface clayey till the stratified sandy loams of number II are well shown in the sides of the bluffs.

Over the mouth of the buried Whirlpool-Saint Davids Channel and extending a short distance westward is the esker-like ridge of sand and gravel rising at one point to 442 feet above the lake. The gravel pits, opened to a depth of 50 feet, show cross-bedding, etcetera,[10] and these deposits have been penetrated to 100 feet or more without change of character.

The Erigan valley and canyon, which formed the ancient outlet of the Erie basin, from 12 to 14 miles west of Niagara Falls, was finally obstructed by an isolated ridge, in many places composed of stratified sandy clays and gravels, but with a till occurring at the summit which is nearly 650 feet above Lake Ontario, while stiff clays are found in the valleys descending to the northward. To the south of this ridge, beneath the covering of 8 feet of clay, the borings were carried to 132 feet, or to 80 feet below the level of Lake Erie, entirely through the quicksand which fills the now buried Erigan Valley. On the ridge Fonthill referred to is a fragment of the Forest beach, or the last shoreline of Lake Warren. Then the kamelike ridge of Lundys Lane, just west of Niagara Falls, is another interesting drift deposit; but these localities require more complete study.

Forest Glen and older Epochs

The key to the relationship of the Pleistocene deposits in the Niagara district was the discovery of the ancient spruce wood, which belongs to a climate cooler than that of the Niagara district of the present day (Penhallow), and to this is to be added the unusual occurrence of the bleached white quartz sand in which wood and twigs still occur. This is simply the soil deoxidized by the decaying vegetable matter. Beneath a depth of about 6 inches it rests on lower undeoxidized soil, also containing twigs with highly oxidized strata just below. These features show that the deep

[10] See work cited before, p. 127.

Whirlpool-Saint Davids Channel was open to a depth of 186 feet below the present surface and was covered by forest. All of the deposits here were brought from the north and were not carried from the Erie basin. Whether the channel was previously filled with drift can not now be known.

The deep trench corresponds to the great interglacial erosion valley found on the north side of Lake Ontario (see below). The spruce wood makes a paleontological connection with the upper Toronto beds. Whatever filling has been removed from the higher portion of the valley was carried away by the local drainage, which excavated it to a depth much lower than the rocky Lyell ridge north of the falls. Still the drift in the buried channel beneath the Forest Glen has been penetrated to a depth of over 100 feet, and it may be double this amount.

So far there are known to be at least two glacial formations older than the Forest Glen and two newer, with apparently a third layer of till before reaching the surface of the plateau, not to speak of the esker-like ridge at the mouth of the ancient gorge. These features place Niagara River near the close of the Pleistocene period, as it cuts through the most recent of the long succession of till formations found in this locality, although the glacial history was not completed in the Saint Lawrence Valley to the northeast.

Correlation of the Whirlpool Drift with that of Scarboro Heights

My investigations of the superficial formations of Ontario were primarily for the study of the deserted beaches, yet in many places there was found evidence of three layers of till, not to mention the morainic ridges. At Scarboro Heights, just east of Toronto, Dr. G. J. Hinde found fossiliferous beds passing below the level of Lake Ontario, in a pre-existing erosion trough, and a bed of till farther west, in Toronto, which he thought passed under the interglacial Scarboro beds. Carved out of them he found great erosion valleys. These were refilled or covered with overlying accumulations of till separated by interglacial beds.[11] Professor Coleman describes a fourth layer of till.[12] From a depth of 41 feet below lake level to 60 feet above, it has been found by the gentlemen before mentioned that the interglacial beds contain flora and fauna indicating a climate similar to that of the present day in a latitude several hundred

[11] But the older till is here as yet only known by the occurrence of the overlying and redeposited beds now forming interglacial series.

[12] See Professor Coleman's papers.

miles to the south of Niagara. Overlying these beds are others containing a flora belonging at present to a belt 200 miles to the north. These occur up to an elevation of 150 feet above Lake Ontario.[13] The fossiliferous beds of both series have been named the Toronto formation by Prof. T. C. Chamberlin. In correlating the fossiliferous beds with the Pleistocene series of the west, Prof. Frank Leverett provisionally thinks that they are newer than the Illinoisan till.

My original measurements of the height of the Iroquois beach just east of Scarboro Heights and those at the mouth of Niagara River show that the post-Iroquois warping amounts to 75 feet; so that, although the Forest Glen deposit occurs at 154 feet above the present lake level, with its correlative back of Toronto at 150 feet, there was an actual difference in height of 79 feet before the warping, but the land surface of the two localities probably varied.

The cool climate beds at Scarboro Heights were dissected by a deep glen, as first pointed out by Hinde, similar to that of the reopened Whirlpool-Saint Davids Valley, before the accumulation of the succeeding Pleistocene deposits, and the phases of erosion and climate are identical in the two localities. Indeed, the amount of erosion was very great. There has been found nothing of similar magnitude on the two sides of the lake. For this epoch of land erosion in the Ontario basin, which would seem to be post-Illinoisan, I apply the name of Forest Glen. This section substantially adds to our knowledge of the Glacial period in the Ontario Valley. The drift below the Forest Glen seems to fill a hiatus between the beds of colder and warmer climate at Toronto, while the warmer beds mentioned should only occur in the Niagara district below lake level, the recent tilting of the land causing the flooding of this region.

Whether the upper series of till above the Forest Glen and those at Toronto are merely alternations of the Iowan and earlier stages of the Wisconsin drift in this region or not, will be left to others to investigate, but the whole series shows that a very nearly complete succession of glacial deposits, except the late Wisconsin, was accumulated in the Niagara district before the birth of the river, which cuts through the most recent till of the region.

Summary

In the borings made in the Whirlpool-Saint Davids Channel, there have been discovered the remains of a cool climate forest and soil at a depth of 186 feet below the surface, with the proof of three or four glacial formations since that time, like the Pleistocene series at Toronto. Before that

[13] Loc. cit.

cool epoch of the Forest Glen, which may be considered a post-Illinoisan, at least two glacial formations have been left in the buried channel, which below is further filled by 100, or perhaps nearer 200, feet of drift, some of the deposits of which may represent a still older Glacial epoch. There seems no reasonable doubt that the ravine at Forest Glen had the same date as the ravines in the fossiliferous beds east of Toronto. The origin of the Whirlpool Gorge is thus shown to be older, by at least two stages, than the fossiliferous beds mentioned (which are supposed by Chamberlin and Leverett to be an equivalent of the post-Illinoisan interglacial period), with still an underlying accumulation of 100 to 200 feet undetermined by direct observation. This lowest drift lies in a rock-bordered valley which has suffered an amount of erosion enormously greater than that during or since the Glacial period. From all the evidence found I can therefore only conclude that this new filled trough is of preglacial origin. The age of the modern Niagara River is also found to be younger than the glacial deposits about the western end of Lake Ontario, though not so recent as the later Wisconsin accumulations in other localities.

Having described the relationship of Niagara River to the older drift deposits, its relationship to the latest ice-sheet should be referred to. Before the birth of the falls, the ice had receded beyond the greatest of all the moraines of Ontario, which lie between Lake Ontario and Lake Simcoe and between this lake and Georgian Bay, a distance of more than 120 miles north of Niagara Falls; so that the drainage of Lake Huron then passed down the Trent Valley, as discovered by the instrumental measurements of the writer in 1888, since confirmed by Gilbert and Taylor, and later remeasured by Goldthwait. From the terrace north of Lake Nipissing, identified by Taylor as belonging to the level of the Algonquin beach, the ice-sheet had receded 230 miles or more to the north of Niagara before the birth of the falls. But the Ottawa Valley farther down was still blocked. The Ontario Valley was also open to at least near the eastern end of the lake, so that it permitted the flow from Algonquin Lake down the Trent Valley, although the ice was not removed from the Saint Lawrence Valley till some time after the birth of the falls. This was the last ice-sheet, concerning which at present we only know that it disappeared so long ago that there was time for the excavation of the inner gorge of Niagara River, extending from Lake Ontario to a point inside the canyon of Niagara, since reflooded and drowned to 180 feet by the subsequent northeastward tilting of the region.

NOTE.—Erigan is the name given to the buried valley and canyon which formed the preglacial outlet of the Erie Valley.

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RELATIVE WORK OF THE TWO FALLS OF NIAGARA

BY J. W. SPENCER

(*Read before the Society December 29, 1909*)

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Preface

The special interest in the Falls of Niagara, apart from the scenic and economic, lies in two scientific directions. One of these is connected with the researches into the remarkable physical changes, not only of the direction of the drainage of the upper lakes, but of the whole lake history and the production of the falls themselves. Although these questions are primarily American, the opportunity is better afforded here than elsewhere of studying the physico-geological problems involved, and hence the falls are of general concern. The other interest is that connected with the age of the falls, as they furnish the best measurements of the amount of geological work that has been performed in a given time, thus becoming a chronometer which, when brought into comparison with the work effected in other localities, will enable us to have definite ideas of glacial time. In this respect the subject is of world-wide interest. Any reasonable variation suggested can only lead to more precise results. To two minor omissions in my previous treatment of the past recession of the Falls of Niagara[1] Dr. G. K. Gilbert has called attention, namely, the work of the American cataract and the variation in the relative effective work of the two falls. These questions I have since partly considered.[2]

Rate of Recession of the American Falls

For want of sufficient time and opportunity and on account of my impression of the relative unimportance of the smaller cataract, I gave but

[1] J. W. Spencer: The Falls of Niagara; their evolution and varying relations to the Great Lakes; characteristics of the power and effects of its diversion. Geological Survey of Canada, 1907, pp. xxxi, 490, with maps and illustrations.
[2] Science, vol. xxviii, 1908, pp. 754-759.

little attention to this topic, which under other conditions would have deserved more prominence. Between the time of the survey by Prof. James Hall, in 1842, and that by Mr. Aug. S. Kibbe, in 1890, there had been only a small recession, and since then apparently so little change had occurred that I did not make a resurvey of them in 1905. My impressions were correct, for by other surveys of 1905[3] and 1906[4] it has been found that scarcely any appreciable amount of rock has fallen. The measurements showed a recession from 1842 to 1890 of 0.60 foot a year, but the average amount from 1842 to 1906 is now found to be 0.45 foot. Originally I stated that since 600 years ago (now corrected to 550 years) "the American Falls do not seem to have retreated more than 110 feet, if so much, in excess of the unknown widening of the gorge from frost action" (page 38). This would represent, if correct, only 0.20 foot a year. This might have left a wide correction for the determination by future generations, but now it can never be done, as the power diversion has already rendered it impossible. Let us put on record how the recession of the smaller falls really compares with that of the main cataract.

While the American cataract suffered a mean recession of only 29 feet between 1842 and 1906 (by actual measurement), the main, or Canadian, Falls retreated 265 feet for a mean breadth of 1,200 feet. Fragments of the original banks are still preserved. As the gross errors of observation are equal in the two cases, these are reduced to a relatively small amount in the latter instance, even though the undercutting before 1842 had considerably progressed. The undercutting in the case of the fallen Table Rock reached from 40 to 50 feet, and nearly the same amount is still to be seen overhanging in front of Wintergreen Flats, some miles down the gorge.

Under these conditions, especially as the superior ledges of hard rocks at the American Falls now project but little, and as there are huge masses of rocks fallen at their foot, it would seem that the undercutting had progressed far when Professor Hall made his survey. This undercutting has caused an excessive amount of collapse of the upper layers of rock since his time, especially as it does not appear how the falls could have receded more than 200 feet since the separation of the two cataracts. All these considerations show that absolute measurements of the recession of the American Falls are not obtainable for calculating the age of the gorge; yet, on the other hand, close estimates of their rate of retreat can be made.

As the diameter of the main falls is 1,200 feet and of the smaller one

[3] By Mr. Basil Hall for the U. S. Geological Survey.

[4] U. S. Lake Survey.

920 feet, exclusive of islands, the rate of 0.45 foot observed since 1842 should be reduced to 0.35 foot if it be compared with the work of the main cataract. At the time of my investigations, engineers generally conceded to the smaller falls 20 per cent of all the water. In opposition, I reduced this to 6 or 7 per cent. It has since been found by the U. S. Lake Survey to be scarcely 5 per cent; so that my results show only a practically negligible error. With a proportional efficiency in recession (as the mean rate at the Canadian Falls is 4.2 feet a year), this would give a theoretical rate of 0.21 foot for the smaller falls; but as this amount of water is acting on only 920 feet of rock face in place of 1,200 feet, for comparative purposes the rate should be raised to 0.27 foot a year, or somewhat greater than was assumed by me (0.20 foot) in "Evolution of the Falls of Niagara."

Again, those calculations are within limits of error, for the falls have decreased their height by 50 or 60 feet since the separation of the two cataracts,[5] which has favored the accumulation of talus at the foot of the American Falls; but Peter Kalm, the naturalist, most positively asserts that their height was 137 feet[6] (French measure), which equals 145 English feet. The reduction in the height of the falls was due to the falling of the gorge walls into the channel at Whirlpool Rapids. Kalm's statement being accepted as correct, it would seem that the Whirlpool Rapids have reduced their height by 22 feet since the year 1750. The lately reduced height of the falls, as mentioned, was finally established from the soundings under the Canadian Falls.

On page 22, in his bulletin on the recession of the falls,[7] Doctor Gilbert suggests that the rate of recession of the American Falls may be 0.32 foot a year, which is near that deduced by me (0.27 foot) as the mean since the separation of the two cataracts. However, these figures are not of value in investigating the age of the falls, as they are not derived from direct measurement, but they are of importance in showing that there is no apparent discrepancy between the relative work of the two falls, and also that any omission of this question did not derogate from the general conclusions as to the age of the Falls of Niagara based on work of the main cataract.

Relative Efficiency of the two Falls of Niagara

This is the other problem omitted from my monograph. In the two cases the rock formations are nearly identical, but the immediate results are very different. The main cataract, falling 158 feet to the cauldron

[5] Op. cit., p. 367.
[6] Op. cit., p. 435.
[7] Bulletin of the U. S. Geological Survey, no. 306, 1907.

below, passes the top of the resistant Clinton limestone (20 to 22 feet thick) at 12 feet above the surface of the basin below the falls, and reaches the blocks of the underlying talus at 72 feet below the surface, as found by my soundings; but the soundings farther away and other features indicate the depth of the river near the falls (where not covered by blocks) to be about 100 feet, although, farther down, the river is deeper, as explained in "Evolution of the Falls" (page 56). Toward the middle of the falls there is no shelf of Clinton limestone, although there is a projecting ledge supporting a talus and extending outward for nearly 1,000 feet from the original edge of the falls on the Canadian side. Here have been two stages in the recession of the rock wall, or an undercutting beneath each of the two series of overhanging limestones.

The conditions at the American Falls are different. They are 167.5 feet high, and the hard Clinton limestones rise to 40 feet above the river at the northern end of the cataract, with the underlying shales also appearing above the river beneath the talus heap of fallen limestones, which also in places rise to more than 40 feet above the lower river; but the fallen mass must be much less than that beneath the water at the foot of the main falls. Thus it would seem that a precise measurement of the relative efficiency in erosion by the two falls is impossible. Add to the difficulty the fact that the falls have changed their height by a reduction from 220 feet to 167 feet, owing to the recently falling rocks at the Whirlpool Rapids forming a dam and raising the surface of the pool below the falls, within the last 300 years, though more than 160 years ago.[8]

Before the time of the rising of the waters in the basin below the falls there was a wall of shales and perishable sandstone layers (70 feet or more in height) beneath the hard Clinton limestones under the American Falls, so that the conditions of recession were much more favorable then than now; but after the rising of the river these lower beds were protected, and with the subsequent collapse of the overhanging walls the accumulated talus became further protective. The talus is now being slowly removed, owing to the direct impact of the falling water, aided by frost action. The observations on the deserted floor of the river at Fosters Flats left the conclusion that the fallen blocks of limestone have been largely carried away by solution.[9] The talus heap under the American Falls (due in part to the undermining by the former higher cataract) is now being worn away with the maximum efficiency, checked only by occasional gales of wind.

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[8] Peter Kalm, writing in 1750, said: "This fall, by all the accounts that have been given of it, has grown less and less, and those who have measured it with mathematical instruments find the perpendicular fall of water to be exactly 137 feet" (French).

[9] Op. cit., pp. 174 and 177.

In contrast, the greater falls impinge on the drowned talus only after they have passed through a stratum of 72 feet of water, forming a very thick cushion, thus diminishing the mechanical effect of the falling water. An effective descent of both falls (allowing for the acquired velocity at their crests) may be taken at 180 feet. Even without knowing the soundings, it would seem improbable that the falls could excavate in the hard shales to 192 feet, as found farther down the gorge, or to a depth beneath the surface of the river greater than the height of the falls. This was rendered still further unlikely by the fact that in the deep channel the hard Medina sandstones had also been penetrated, while now the soundings show that the present descent of the falling water does not penetrate them.[10] Thus while the full efficiency of the American Falls is at work on the exposed rocks and talus masses, a third, or perhaps more, of the effective force of the great mass of water of the Canadian Falls is lost in friction, heat, and the counterbalancing hydrostatic pressure of the river.

While there is still some current when the falls reach the talus at a depth of 72 feet, yet it is broken up on the talus, just as is seen above the river surface below the American Falls, and it soon loses its greater mechanical effect among the fallen blocks; but the chemical solution by the circulating currents, which can no longer shift the blocks, is most active; else the talus heap would grow so as to produce rapids in place of falls. Such results may be seen at some small cataracts.

Some unfinished experiments of falling water in which I had the opportunity of taking part led me to conclude that when the descent is like that of a rapid, a gentle current may reach to a considerable depth, slowly moving fine particles, as in the deeper holes of a stream where alluvium is being deposited; but when the descent is by a considerable fall into a basin, the blow is so checked that the current capable of moving fine sand reaches approximately to only two-thirds of the descent of the fall above the surface of the basin. The experiments were made on already loose materials, and it seems to me that the relative result would be further reduced where the force of abrasion is applied to solid rocks.

Observations and measurements made in determining the efficiency of a water power where the water descends 208 feet in a penstock of 3 feet diameter, having an inclined position, gave the gross amount of work as 1,631 horsepower, while the relative efficiency when using the full volume of water was 78.5 per cent; but when using only from 90 to 67 per cent of the water it actually rose to 80 per cent, thus showing greater power where there was some freedom in the tube. Using 50 per cent of the water, the efficiency fell only to 76 per cent, or 2½ below that of the greatest power. The use of 40 per cent yielded 70; 30 per cent brought

[10] Op. cit., pp. 56-58.

the efficiency down to 60, below which the loss through friction in the inclined pipe and turbine was relatively still greater. But this mechanical contrivance, using only about 70 cubic feet per second in a relatively small pipe, can not be compared with the free flow of 10,000 cubic feet per second, as in the case of the American Falls, where there is neither tube friction nor turbine losses.

The reason for comparing the relative work accomplished by the two falls lies in the fact that throughout the greater life of Niagara the discharge was more nearly like that of the American than of the Canadian Falls. At that time the volume was three times as great as the present American Falls, but the mean height of the uppermost cataract on which the determinations were made was only seven-twelfths that of the effective height of the American Falls; so that the work performed was less than double that of the present smaller cataract. There is no suggestion of any retardation in the lower river, but the lake level probably held back the river so that there would be a pool at the foot of the falls of a few feet in depth, as is commonly seen elsewhere; but the pool was above the surface of the Medina sandstone and perhaps its depth may not have exceeded 10 feet. At one time the river was well drained when the lake was much lower than now, although later it backed up and drowned the deeper channel described in "Evolution of the Falls of Niagara." The basin below the main cataract now forms a safety balance, as it were, being excavated to a depth according to the mechanical force of the falls,[11] and it appears to me that a similar balance has always maintained, else with the direct action on the bottom rocks, like at the American Falls, the relative efficiency in erosion would be greater than that of the Canadian Falls descending into its deep basin, thereby losing much of its power. The frost action at the smaller falls, as pointed out by Prof. James Hall, is greater than under a great sheet of water.

Whether the work performed by the changing conditions of the Falls of Niagara be within 10 per cent of that computed or require a correction of double this amount or more, the investigations give us an approximate result, based on direct measurements and not on mere opinions or hypotheses. There now seem to be no important omissions in the determination of the changing work of the falls. It was well to raise the questions here discussed, and this paper is offered as an additional chapter to the monograph on the Falls of Niagara, and the analysis of the features here considered strengthens the conclusions previously reached. They show that there is a balance maintained in the relative depth of the pool beneath the retreating cataract.

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[11] The variable depth of the river corresponds to the loss of erosion, as shown in the work cited, pp. 344, 350, 351.

AMERICAN FALLS

1,000 feet long, frozen and drained February 17, 1909 (Spencer)

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INTERRUPTION IN THE FLOW OF THE FALLS OF NIAGARA IN FEBRUARY, 1909

BY J. W. SPENCER

(Read before the Society December 29, 1909)

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Previous Fluctuations

Since the year 1890, the mean level of Lake Erie has fallen about 1 foot[1] and the basin above Goat Island about a foot and a half. From that year until the end of 1905, the mean annual fluctuations varied scarcely more than 1 foot, while in one case the mean monthly variation reached nearly 2 feet; but during the progress of storms, when the wind has changed to the opposite direction, the fluctuations have been found to reach 5 or even 6 feet.

Fluctuations of 1909

During January and the early part of February, 1909, the lake level was below that of the mean, but on February 10 Lake Erie rose nearly 3 feet above the mean annual average height (1889-1905, inclusive), while in the following and succeeding days it fell with a northerly wind to 4 feet below the mean (as shown by the records of the gauges as furnished the U. S. Lake Survey). This was on February 14. At this time the weather was very cold. On account of the reduced depth of the water on the upper rapids, as the ice was forming, it remained anchored to the projecting rocks and was not carried over the falls; so that the New York channel and the main channel to about 600 feet outside of Goat Island were frozen over, except one small lead, which scarcely showed any current where ordinarily it is a rushing torrent. It must be emphasized that the ice was not an accumulation of blocks carried down from Lake Erie, as often occurs, like in the jam of the following April. As the blizzard con-

[1] J. W. Spencer: Evolution of the Falls of Niagara. Geological Survey of Canada, p. 190.

tinued, with its falling snow, the lake level fell to the lowest on February 14, and almost all of the water beneath the ice was withdrawn, so that the American Falls of 1,000 feet in breadth were drained, except four or five insignificant streamlets, as shown in plate 32. The eastern side of the main falls, adjacent to Goat Island, was drained for 800 feet, as may be seen in plate 33, figure 1. The end of the ice-covered rock rim of the first cascade of the upper rapids, with the frozen river in front of Goat Island, is shown in plate 34, figure 1. On the Canadian side, the main falls, which have already been curtailed by 415 feet, due to power diversion, was further drained by about 200 feet, as illustrated in plate 33, figure 2. Another photograph, not reproduced, shows that in the middle of the main cataract the rocks almost reached the surface; but without allowing for these thinly covered masses, the total shrinkage of the main falls amounted to a reduction of tne crest line from 2,950 feet (in 1901) to 1,600, and the diameter was shortened from 1,200 feet to less than 800.

From the foregoing it may be understood that the cause of Niagara "running dry," as expressed by the newspapers, was due to the recent lowering of the river level (partly owing to power diversion), thus permitting the formation of the ice-barriers, which cut off the reduced supply of water during a strong northerly wind, in very cold weather, at a time of the low stages of Lake Erie. This condition continued for nearly a week. Had there been no ice, the extreme effect of the wind would have lasted for only a day, even if the volume of water had been below the normal amount. The Whirlpool Rapids were lowered by many feet, so that the usual rushing, boiling, pitching, torrents seemed tamed, as may be seen in plate 34, figure 2.

Similar Occurrences

Within the historic record the only other times when similar phenomena have been seen were the following: On March 29, 1848, the ice from Lake Erie blocked the river for one day, as described by the Hon. Peter A. Porter; on March 22, 1893, a partial stoppage occurred, which also appeared to have been due to the blockade of lake ice; and on February 29, 1896, there was another shrinkage of the falls. None of these cases were comparable to that of 1909, when the phenomena lasted for nearly a week from February 14. With the continued draining of the falls, a repetition of these features should be expected. In part, they represent what will become a permanent condition, owing to power diversion. The above is from my personal observations, and the photographs are of my taking or those of Mr. E. Deming Smith, of Niagara Falls, who accompanied me.

Note.—In March, 1910, owing to the shoaling of the waters on the upper rapids, the ice was caught and so barricaded the New York channel that the American Falls were again damaged, being broken into four parts.

FIGURE 1.—GOAT ISLAND END OF MAIN OR CANADIAN FALLS

Drained February 16, 1909 (Spencer)

FIGURE 2.—WESTERN END OF MAIN FALLS

Already curtailed by length of wall. Further drained February 16, 1909 (Spencer)

PORTIONS OF NIAGARA FALLS

FIGURE 1.—END OF ICE-COVERED AND DRAINED RIM OF FIRST CASCADE OF UPPER RAPIDS, ABOVE THE "SISTER ISLANDS," FEBRUARY 17, 1909 (SMITH)

FIGURE 2.—WHIRLPOOL RAPIDS, AT VERY LOW WATER, FEBRUARY 17, 1909 (LOOKING DOWNWARD) (SMITH)

PORTIONS OF NIAGARA FALLS

FIGURE 1.—NEWLY CLEARED FIELD COVERED WITH MOUNDS OF ANTS NEAR RIO UTINGA, STATE OF BAHIA, BRAZIL

The largest of these mounds have bases of six or seven meters. Photograph by R. Crandall, 1907

FIGURE 2.—MOUNDS OF TERMITES IN AN OLD FIELD NEAR QUELUZ, STATE OF MINAS GERAES, BRAZIL

White spots in the background are the mounds. Photograph by Dr. Gonzaga de Campos, 1909

MOUNDS MADE BY ANTS AND TERMITES: BRAZIL

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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GEOLOGIC WORK OF ANTS IN TROPICAL AMERICA[1]

BY J. C. BRANNER

(*Read before the Cordilleran Section of the Society March 25, 1910*)

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[1] Manuscript received by the Secretary of the Society April 29, 1910.

Introductory

In 1900 I published a short paper on the geologic work of ants in the tropics.[2] Since then a good many additional observations, notes, and photographs have been made, and the most important of them are here brought together in a single article.

There are many brief notes on the work of ants scattered through the writings of travelers in tropical countries, but these notes are for the most part repetitions of rather vague and sensational stories which make no claim to accuracy of statement, so that they would add little or nothing to the value of the article. No attempt has, therefore, been made to use such notes except in so far as they seem to afford new or important corroborative evidence. At the same time it is realized that some of the things that ants do in tropical countries are so remarkable that those who have no personal experience of them may be pardoned for regarding the stories told about them with a certain amount of suspicion. For this reason I have quoted directly, and sometimes at considerable length, from some of our most trustworthy scientific writers, especially from Bates, Belt, and Spruce, all of whom are naturalists to be taken seriously.

The best any one can do who has not seen the work of ants in tropical countries is to turn to what can be seen in temperate regions. But it should be insisted on that the work done by ants in temperate zones is, with a few exceptions, of no geologic importance at all as compared with that done by them in some parts of the tropics.

The work of the ants, in so far as it is of geologic importance, consists chiefly of their nests, habitations, refuse heaps, or mounds, above ground and their burrows, tunnels, passageways, and other excavations beneath the surface, and the opening up of the soil and the subjacent rocks to the various atmospheric influences.

In the United States we have very little evidence of ants making either underground passageways or mounds of sufficient size or extent to have attracted much attention. Indeed, it seems to be generally conceded by entomologists that the ants of the northern part of North America are not as enterprising as those farther south, or even as those of Europe. Forel seems to have found the structures of our North American ants so insignificant that he avoided speaking of them as having mounds at all. Certainly the little ant-hills we have seen in most parts of the United States are too insignificant to attract the attention of geologists. In the South and Southwest they are somewhat more conspicuous, and in the semi-arid portions of western Texas and in Arizona, New Mexico, and parts of California they have attracted not a little attention.

[2] Journal of Geology, vol. viii, pp. 151-153. Chicago, 1900.

The western halves of Oklahoma, Kansas, and Nebraska and the eastern portion of Colorado are inhabited by mound-building prairie ants that are sufficiently abundant and sufficiently pugnacious to have attracted the attention of farmers and entomologists, if not of geologists.[3]

In the Western States generally ants are more abundant than they are in the East, but a writer on the ant-hills of southwestern Wisconsin says that in that part of the country he knows of at least a hundred so-called ant-hills within a radius of 5 miles, and he appears to regard this number as quite striking. Their mounds, he says, are as much as 75 centimeters in diameter and 40 centimeters in height.[4] These cases are mentioned simply for the purpose of contrasting the size and number of ant-hills in a region that seems to be regarded as pretty thickly inhabited with some of the typical localities in the tropical portions of South America.

Furthermore, in the tropical parts of America ants are not the simple and easily ignored insects with which we are acquainted in the temperate zones of the earth. Save in the cities, they are almost omnipresent. To the housekeeper they are not only never-sleeping pests, but they are bold and defiant robbers or sneak thieves, as circumstances require, and they can not be ignored. To the planters they are veritable plagues—they destroy the growing crops as completely as if they had been burned over. They do not wipe out a field of grain in a few hours as completely as do the locust swarms of Argentina, and then disappear, but they stay with their work right alongside of the crops, and with time they destroy them no less certainly. Unlike the locusts, they do not come and depart, but they stay right in one circumscribed area all their lives. *Farinha de mandioca,* the meal prepared from the cassava plant, or grain of a size small enough for them to carry, require to be guarded with constant care. I have known bagfuls of farinha de mandioca to be carried away by them. In short, the inhabitants have to be constantly on their guard against the ants, both indoors and out of doors, to say nothing of the mere inconvenience of their presence. Nor can their importance be regarded as whimsical in any sense; indeed, I am convinced that they are social, and even national, factors that are not to be ignored.

Nothing in the way of a biologic or systematic study of tropical ants is attempted in the present paper. However valuable such a study might be, it is the number of individuals, rather than the number of species, that concerns the geologist, though it is recognized, of course, that some

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[3] T. J. Headlee and George A. Dean: The mound-building prairie ant (*Pogonomyrmex occidentalis* Cresson). Bull. 154, Kansas Agricultural Experimental Station. Manhattan, 1908.

[4] Hermann Muckermann: Psyche, vol. ix, pp. 355-360. Boston, 1902.

species are much more active agents than others. We need concern ourselves with only two large orders: the true ants belonging to the *Hymenoptera*, and the termites, or so-called white ants, neuropteroid insects which belong to the *Isoptera*, and are known all over Brazil by the popular Indian name of "cupim." And nothing is attempted in the way of a study of the architecture of their nests and underground passages, save in so far as such details will give a better idea of the geologic bearing of these matters.

The monumental work of Dr. Auguste Forel, "Les Fourmis de la Suisse," published at Zurich in 1874, will naturally be consulted by any one especially interested in ants themselves and in their habits and structures.

It may be useful to suggest in this connection, however, that though the ants of Switzerland and of temperate regions generally exhibit the same ingenuity and intelligence as those of tropical countries, as geologic agents they are very tame indeed in comparison with those of the tropics.

In studying the work of ants in the tropics one is constantly reminded of Mr. Darwin's studies of the work of earthworms. Mr. Darwin was able to give the quantitative results of his studies. In the case of the ants, unfortunately, quantitative results have not been possible. The time occupied by them in doing a given amount of work varies so much that quantitative observations, in order to have any value, would have to be carried on upon many colonies and for a long period of time. The results given at page 469 are an attempt at quantitative determination, but it will be observed that it is not known how many individuals took part in the work, while the time element involved in the calculation is entirely lacking. It is hoped that observations may be undertaken by geologists living in tropical countries with a view to settling these interesting points.

To illustrate this article especial pains have been taken to get as many photographs and sketches as possible of the above-ground structures of ants and termites, and the accompanying illustrations have been carefully made by Mrs. Starks from photographs, most of them taken in Brazil by myself or by my former assistant, Mr. Roderic Crandall, now geologist of the Geological Survey of Brazil (Serviço Geologico do Brazil). It seemed better to have the drawings made rather than to use the original photographs, in spite of the evident suspicion of exaggeration or alteration, whether intentional or accidental, to which all drawings are open. This redrawing was the more necessary because the photographs were taken hastily and under many unfavorable circumstances, and they are therefore often not good, or they are not available for reproduction as photographs, besides being of various inconvenient sizes. The illustrations are given because it is felt that they are the most impressive and most trustworthy witnesses one can put in evidence regarding the subject.

The true Ants

ABUNDANCE

Atlhough ants are not everywhere equally abundant in tropical South America, their numbers are so large on an average as to promptly attract the attention of travelers, even when they do not excite their wonder. Residents, who might be expected to have conservative views on the subject, often speak of them as the owners of the land. Such a remark is at first regarded as merely facetious, but the character of some of the writers who make it entitles it to serious consideration. As long ago as 1648 Piso said that the Portuguese not inappropriately called the ant the "king of Brazil."[5]

One naturalist who spent some time in the country says, "Brazil is one great ants' nest."[6]

Belt says, "They are one of the greatest scourges of tropical America."[7]

A Brazilian traveler, speaking of the region of the upper Rio, Paraguay, says, "The ant and the different kinds of termites own the land."[8]

Another puts it in this fashion: ". . . ants . . . deserve to be considered the actual owners of the Amazon Valley far more than the red or the white man."[9]

Another writer says of them: "One seriously asks whether they are not the real conquerors of Brazil."[10]

These characterizations are all so sweeping that, taken alone, they are open to the suspicion of being merely picturesque and extravagant ebullitions rather than serious and truthful statements of fact. If they are based on some knowledge of the ants, these expressions seem to spring from more or less personal animosity toward those insects. And yet this very animosity, if it really exists, must come from a pretty uniform per-

[5] Formicæ autem hæ (*Rey do Brasil* Lusitanis non immerito dictæ, quod perpetuam tyrannidem exerceant) aliquæ Europæarum planc similes, aliquæ triplo majores & alatæ, omnivoræ sunt.

De Aeribus, Aquis, & Locis. Gvilielmi Pisonis Historiæ Naturalis & Medicæ, p. 9. Amsterdam, 1658.

[6] Rev. H. Clark: Letters home from Spain, etc., pp. 131, 173. London, 1867.

[7] Thomas Belt: The naturalist in Nicaragua, p. 79. London, 1874.

[8] Dr. Joao Severiano da Fonseca. Viagem ao redor do Brazil, vol. i, p. 352. Rio de Janeiro, 1880.

[9] Richard Spruce: Notes of a botanist on the Amazon and Andes, vol. ii, p. 366. London, 1908.

[10] Adolph d'Assier: Revue des Deux Mondes, vol. xlix, p. 582. Paris, 1864.

sonal experience of them. It therefore seems best to quote directly a few more detailed statements regarding the abundance and habits of ants in Brazil. Certainly no one will be taken more seriously than Dr. Auguste Forel, who says that "the ant fauna of South America is perhaps the richest in the world from the systematic point of view."[11] In the paper cited 440 species of true ants are noted as inhabiting Brazil, out of a total of 2,000 known in the world.

But though it is with the number of individuals rather than the number of species that we are concerned, it is worth remembering that in many considerable regions a single species may occupy about all the ground space that it is possible for ants to occupy. A single species may thus fairly swarm and do a vast deal more work than several different species.

The true ants, evidently of a large number of species, are so abundant and are such serious pests in some places that the land is practically preempted by them. Travelers passing the night in the open have to be constantly on their guard against colonies of ants. Fighting such colonies under the circumstances is simply out of the question. When one finds himself in disagreeable proximity to them, the only thing to be done is to move at once and leave the ants masters of the situation.

Bates, speaking of a certain species, says (page 354):

"These Ecitons are seen in the pathways of the forest at all places on the banks of the Amazons, traveling in dense columns of countless thousands."

On the Rio Tapajos, in the Amazon Valley, Bates noted the

"quantity of drowned winged ants along the beach; they were all of one species, the terrible *formiga de fogo* (*Myrmica sævissima*), the dead or half-dead bodies of which were heaped up in a line an inch or two in height and breadth, the line continuing without interruption for miles at the edge of the water. The countless thousands had been doubtless cast into the river while flying during a sudden squall the night before, and afterwards cast ashore by the waves."[12] . . . "I was told that this wholesale destruction of ant-life takes place annually, and that the same compact heap of dead bodies which I saw only in part extends along the banks of the river for 12 or 15 miles" (op. cit., p. 206).

I have seen similar accumulations of dead female ants on the lower São Francisco and the Rio Paraguay, near Corumba, and at two places on the shores of estuaries near Aracaju, in the State of Sergipe.

Bates says the *formiga de fogo*, or fire ant, was so abundant at one

[11] A. Forel: A fauna das formigas do Brazil. Bol. do Museu Paraense, vol. 1, p. 89. Pará, 1895.

[12] H. W. Bates: The naturalist on the River Amazons, 4th ed., p. 201. London, 1875.

place on the Tapajos that there was scarcely a square inch of ground free from them. (Op. cit., p. 202.)

The only figures I am able to give in regard to the sizes of ant colonies are the estimates given by Azevedo Sampaio, a Brazilian entomologist who has studied the *saúbas*. He estimates the colonies at from 175,000 to 600,000 individuals.[13]

DESTRUCTIVENESS

In speaking in general terms of the destructiveness of ants in tropical America, Humboldt says:[14]

"Those who do not know the immense quantity of ants that infest every country within the torrid zone, can scarcely form an idea of the destruction and of the sinking of the ground occasioned by these insects. They abound to such a degree on the spot where Valencia is placed that their excavations resemble subterranean canals, which are filled with water in the time of the rains and becomes very dangerous to the builders. Here recourse has not been had to the extraordinary means employed at the beginning of the sixteenth century in the island of St. Domingo, when troops of ants ravaged the fine plains of La Vega and the rich possessions of the order of St. Francis. The monks, after having in vain burnt the larvæ of the ants, and had recourse to fumigations, advised the inhabitants to choose by lot a saint, who would serve as an *abagado contra las hormigas*. The honour of the choice fell on St. Saturnin, and the ants disappeared as soon as the first festival of this saint was celebrated. Incredulity has made great progress since the time of the conquest, and it was on the back of the Cordilleras only that I found a small chapel, destined, according to its inscription, for prayers to be addressed to Heaven for the destruction of the *termites*."

The destruction wrought by the true ants is confined chiefly, but not entirely, to agricultural products. It is no uncommon thing to find spots where certain ants are so abundant and so destructive that the planters simply leave them alone. Sometimes it happens that after clearing a piece of land, and beginning their planting, the farmers find the ants so destructive that those particular fields are abandoned. In the coffee regions certain ants, popularly known as the *saúbas*, are so destructive that a systematic and unceasing war has to be waged upon them in order to save the coffee trees. But their attacks are not confined to coffee trees by any manner of means.

The following description of the *saúbas* is given by Gabriel Soares de Souza, one of the earliest writers on Brazil (1587).[15]

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[13] Azevedo Sampaio: Sauva ou Manhu-uâra, pp. 50, 54. S. Paulo, 1894.

[14] Alexander de Humboldt and Aimé Bonpland: Personal narrative of travels to the equatorial regions of the new continent, vol. iv, p. 191. London, 1819.

[15] Gabriel Soares de Souza: Tratado descriptivo do Brazil em 1587. Revista do Instituto Historico do Brazil, vol. xv, p. 271. Rio de Janeiro, 1851.

What is said of that period is equally true today:

". . . Wherever they go they destroy the fields of mandioca, the orchards, orange trees, pomegranates, and vines. If it were not for these ants there would be many Portuguese vines and grapes in Bahia. These ants come a long way at night to find a mandioca field, and where they march they wear a path as if people had walked along it for many days, and they never go out except by night. And in order to prevent their eating the trees which they injure, a ring of mud is put around their bases and filled with water, and if the water dries up during the day, or if a straw falls across it in the night they have spies who notify them at once, and immediately such a multitude of them crosses over on the straw that before morning they have all the leaves on the ground; . . . and while everything grows here that can be desired, this curse interferes to such an extent that it takes away men's desire to plant any more than that without which they can not live."

A late and thoroughly trustworthy writer says of the ants in the coffee regions:

"The enemy most dreaded in the fazendas is indubitably the sauva, or tanajura, a dark-brown ant, two centimeters long, which undermines the ground by digging extensive passages and dens in all directions. It attacks all sorts of trees, the coffee-shrub among others, but has a decided preference for the orange and citron trees in the coffee gardens.

"In former times these ants seem to have worked frightful havoc in the cafesaes (coffee plantations) by causing landslips, because the means of destroying whole nests at once was not then discovered. Now they are less feared, although it still costs from 8 to 12 guineas a month per plantation to keep them down.

"On every fazenda two or three slaves are kept, whose exclusive business it is to find out the nests of the sauvas. Frequently they are even paid a certain sum to encourage and quicken their zeal. . . .

"The subterranean ant-labyrinth destroyed in my presence near the fazenda areas in Cantagallo seemed to be very extensive."[16]

The expense of fighting these ants is a really serious item in the cost of the production of Brazilian coffee. A distinguished Brazilian planter says, with perfect justice, that "among the obstacles with which the planters have to contend . . . there stands perhaps in the front rank the destructive force represented by the *saúba*."[17]

One can get some idea of the economic importance of ants in Brazil from the fact that in the 70's and early 80's an enormous number of privileges or patents were asked of the Brazilian government for machines and devices of various kinds for killing ants, and especially the *saúbas*.

[16] C. F. Van Delden Laërne: Brazil and Java. Report on coffee culture in America, Asia, and Africa, pp. 297-298. London, 1885.

[17] Henrique de Paula Mascarenhas: Revista Agricola do Imperial Instituto, vol. xiv, p. 215. Rio de Janeiro, December, 1883.

In 1857 the province of Rio de Janeiro voted a reward of $25,000 for the discovery of a means of destroying *saúbas*.[18]

The growing of oranges, roses, and other flowering plants is similarly interfered with in many places because of the cutting and carrying away of the leaves by the *saúbas*.

It is impossible to keep things out of their reach on any large scale. Certain devices are used with more or less success for protecting things indoors when they are constantly watched, but standing crops or considerable stores require constant watchfulness and war.

Bates has the following in regard to the *saúbas* in the Amazon region:

"This ant (the *saúba*) is seen everywhere about the suburbs, marching to and fro in broad columns. From its habit of despoiling the most valuable cultivated trees of their foliage, it is a great scourge to the Brazilians. In some districts it is so abundant that agriculture is almost impossible, and everywhere complaints are heard of the terrible pest."[19]

At another place (page 11) he says:

"Besides injuring and destroying young trees by despoiling them of their foliage, the *saúba* ant is troublesome to the inhabitants from its habit of plundering the stores of provisions in houses at night, for it is even more active by night than in the daytime. At first I was inclined to discredit the stories of their entering habitations and carrying off grain by grain the farinha, or mandioca meal, the bread of the poorer classes of Brazil. At length, while residing at an Indian village on the Tapajos, I had ample proof of the fact. One night my servant woke me three or four hours before sunrise by calling out that the rats were robbing the farinha baskets, the article at that time being scarce and dear. I got up, listened, and found the noise very unlike that made by rats, so I took the light and went into the storeroom, which was close to my sleeping place. I there found a broad column of saúba ants, consisting of thousands of individuals, as busy as possible, passing to and fro between the door and my precious baskets" (p. 12). "My servant told me that they would carry off the whole contents of the two baskets (about two bushels) in the course of the night if they were not driven off."

ATTACKS ON MAN

The *formiga de fogo*, or fire ants, are so called on account of the painfulness of their sting. When they are met with in large numbers there is simply no withstanding them.

One of the reasons for calling ants the kings, rulers, and owners of the country is due to the vicious attacks they make upon all kinds of animals. Bates tells of one case in which a town on the Tapajos was actually

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[18] Auxiliador da Industria Nacional, vol. xxxvii, p. 64. Rio de Janeiro, 1869.
[19] H. W. Bates: The naturalist on the River Amazons, 4th ed., p. 9. London, 1875.

depopulated by ants of this kind. This statement seems so remarkable that it is quoted here at length:[20]

"Aveyros was deserted a few years before my visit on account of this little tormentor (*formiga de fogo*), and the inhabitants had only recently returned to their houses, thinking its numbers had decreased. It is a small species, of a shining reddish colour, not greatly differing from the common red stinging ant of our own country (*Myrmica rubra*), except that the pain and irritation caused by its sting are much greater. The soil of the whole village is undermined by it; the ground is perforated with the entrances to their subterranean galleries, and a little sandy dome occurs here and there, where the insects bring their young to receive warmth near the surface. The houses are overrun with them; they dispute every fragment of food with the inhabitants, and destroy clothing for the sake of the starch. All eatables are obliged to be suspended in baskets from the rafters and the cords well soaked with copauba balsam, which is the only means known of preventing them from climbing. They seem to attack persons out of sheer malice; if we stood for a few moments in the street, even at a distance from their nests, we were sure to be overrun and severely punished, for the moment an ant touched the flesh he secured himself with his jaws, doubled in his tail, and stung with all his might. When we were seated on chairs in the evenings in front of the house to enjoy a chat with our neighbors, we had stools to support our feet, the legs of which, as well as those of the chairs, were well anointed with the balsam. The cords of hammocks are obliged to be smeared with the balsam in the same way to prevent the ants from paying sleepers a visit."

In order to give a clear understanding of the seriousness of the bite of these ants, I quote the following from Dr. Richard Spruce's personal experience of them:

"Aug. 15, 1853.—Yesterday I had the pleasure for the first time of experiencing the sting of the large black ant called tucandera in Lingoa Geral. . . .

"I had gone after breakfast to herborise in the caapœra north of San Carlos, where there were a good many decayed trunks and stumps. I stooped down to cut off a patch of a moss on a stump, and remarked that by so doing I exposed a large hollow in the rotten wood; but when I turned me to put the moss into my vasculum I did not notice that a string of angry tucanderas poured out of the opening I had made. I was speedily made aware of it by a prick in the thigh, which I supposed to be caused by a snake until, springing up, I saw that my feet and legs were being covered by the dreaded tucandera. There was nothing but flight for it, and I accordingly ran off as quickly as I could among the entangling branches, and finally succeeded in beating off the ants, but not before I had been dreadfully stung about the feet, for I wore only slippers without heels, and these came off in the struggle. I was little more than five minutes' walk from my house, . . . and I wished to walk rapidly, but could not. I was in agonies, and had much to do to keep from throwing

[20] Naturalist on the Amazons, p. 205.

myself on the ground and rolling about, as I had seen the Indians do when suffering from the stings of this ant. I had in my way to cross a strip of burning sand, and then to wade through a lagoon, partly dried up, and not more than two feet deep. Both these increased the torture; I thought the contact with the water would have alleviated it, but it was not so.

"When I reached my house I immediately had recourse to hartshorn. No one was near but an Indian woman, . . . and she, without my telling her, . . . bound a ligature tightly above each ankle. After rubbing for some time with the hartshorn and experiencing no relief, I caused her to rub with oil, and then with oil and hartshorn mixed. None of these seemed to have any effect; when the oil was made hot it relieved me a little, but very little, indeed, and the wounds which were least rubbed ceased to pain me the soonest, one that had not been touched being the first cured.

It was about 2 p. m. when I was stung, and I experienced no alleviation of the pain till 5. During all this time my sufferings were indescribable. I can only liken the pain to that of a hundred thousand nettle-stings. My feet and sometimes my hands trembled as though I had the palsy, and for some time the perspiration ran down my face from the pain. With difficulty I repressed a strong inclination to vomit. I took a dose of laudanum at 4, and I think this did more than anything to lull the pain. I had been stung on the two big toes and on the soles of my feet, but the stings that caused me most suffering were four close together among the fine veins below the left ankle. When the pain of all the others had subsided this continued to torment me, and pains shot from it all over the forefoot and some way up the leg, notwithstanding the bandages.

"After the pain had become more bearable, it returned with great force on two occasions, at 9 o'clock and at midnight, when I stepped out of my hammock on my left foot, and each time caused me an hour of acute suffering. Towards morning I slept, and when I woke up I felt no inconvenience beyond a slight numbness in the feet, but the inflammation continued unabated for thirty hours. It is curious that nothing was visible externally more than would be caused by the stinging of an ordinary nettle. Possibly swelling was prevented by the application of the hartshorn and oil, for I have heard of cases where the swelling was considerable. Rubbing in the ingredients served to increase the pain both at the time and afterwards."[21]

BENEFICIAL ANTS

Not all the ants are to be looked upon as pests. Certain carnivorous ants are rather to be regarded as beneficial to agriculture, and to mankind generally, on account of their destruction of caterpillars and other noxious insects. In districts where cotton is grown the larvæ of the cotton moths are kept in check by the ants destroying the young ones, especially during the early part of the season. The invasion of houses by ant colonies is a common occurrence in every part of Brazil. Ordinarily these invasions are only temporary. During the hour or two when these

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[21] Richard Spruce: Notes of a botanist on the Amazon and Andes, vol. i, pp. 362-364. London, 1908.

ants swarm through one's house or rooms they are certainly annoying, but they soon disappear, and one feels that he has been relieved to a considerable extent from the cockroaches and other more offensive and serious plagues.

Many writers have described the operations of these ants, but the following, quoted from Dr. Richard Spruce, will give a clear idea of these operations:[22]

"Ecitons, or foraging ants (called Cazadoras in Peru), seem to be true wandering hordes, without a settled habitation, for a certain number of them may always be seen carrying pupæ, apparently of their own species; but they sojourn sometimes for several days whenever they come upon suitable food and lodging.

"The first time I saw a house invaded by Cazadoras was in November, 1855, on the forest slope of Mount Campana, in the eastern Peruvian Andes. I had taken up my abode in a solitary Indian hut, at a height of 3,000 feet, for the sake of devoting a month to the exploration of that interesting mountain. The walls of the hut were merely a single row of strips of palm trees, with spaces between them wide enough to admit larger animals than ants. One morning soon after sunrise the hut was suddenly filled with large blackish ants, which ran nimbly about and tried their teeth on everything. My charqui proved too tough for them; but they made short work of a bunch of ripe plantains, and rooted out cockroaches, spiders, and other such like denizens of a forest hut. So long as they were left unmolested they avoided the human inhabitants; but when I attempted to brush them away they fell on me by hundreds and bit and stung fiercely. I asked the Indian's wife if we had not better turn out a while and leave them to their diversions. 'Do they annoy you?' said she. 'Why, you see it is impossible for one to work with the ants running over everything,' replied I. Whereupon she filled a calabash with cold water, and, going to the corner of the hut where the ants still continued to stream in, she devoutly crossed herself, muttered some invocation or exorcism, and sprinkled the water gently over them. Then walking quietly round and round the hut, she continued her aspersion on the marauders, and thereby literally so damped their ardour that they began to beat a retreat, and in ten minutes not an ant was to be seen.

"Some years afterwards I was residing in a farm-house on the River Daule, near Guayaquil, when I witnessed a similar invasion. The house was large, of two stories, and built chiefly of bamboo-cane, the walls being merely an outer and an inner layer of cane, without plaster inside or out, so that they harboured vast numbers of cockroaches, scorpions, rats, mice, bats, and even snakes, although the latter abode chiefly in the roof. Notwithstanding the size of the house, every room was speedily filled with the ants. The good lady hastened to fasten up her fresh meat, fish, sugar, etc., in safes inaccessible even to the ants, and I was prompt to impart my experience of the efficacy of baptism by water in ridding a house of such pests. 'Oh!' said she, laughingly, 'we know all that; but let them first have time to clear the house of vermin,

[22] Richard Spruce: Notes of a botanist on the Amazon and Andes, vol. ii, pp. 371-373. London, 1908.

for if even a rat or snake be caught napping they will soon pick his bones.' They had been in the house but a very little while when we heard a great commotion inside the walls, chiefly of mice careering madly about and uttering terrified squeals; and the ants were allowed to remain thus and hunt over the house at will for three days and nights, when, having exhausted their legitimate game, they began to be troublesome in the kitchen and on the dinner table. 'Now,' said Dona Juanita, 'is the time for the water cure,' and she set her maids to sprinkle water over the visitors, who at once took the hint, gathered up their scattered squadrons, reformed in column, and resumed their march. Whenever their inquisitions became troublesome to myself during the three days, I took the liberty to scatter a few suggestive drops among them, and it always sufficed to make them turn aside; but any attempt at a forcible ejectment they were sure to resent with tooth and nail, and their bite and sting were rather formidable, for they were large and lusty ants. For weeks afterwards the squeaking of a mouse and the whirring of a cockroach were sounds unheard in that house." (Footnote.)

"The ants called Carniceras, or butchers, in Maynais are probably of a tribe distinct from the foragers, for they are burrowing ants, and are said to prefer the flesh of human carcasses to any other food. Padre Velasco, in his *History of Quito*, assures us that they will make a perfect skeleton of a corpse the very day it is buried, and that they devour any disabled animal, however large, they find in the forest."

Thomas Belt has a good deal on the swarms of ants in Central America. The following extract is from his "Naturalist in Nicaragua," page 17:

"One of the smaller species (*Eciton predator*) used occasionally to visit our house and swarm over the floors and walls, searching every cranny and driving out the cockroaches and spiders, many of which were caught, pulled, bitten to pieces, and carried off. The individuals of this species were of various sizes, the smallest measuring one and a quarter lines and the largest three lines, or a quarter of an inch.

"I saw many armies of this, or a closely allied species, in the forest. My attention was generally first called to them by the twittering of some small birds, belonging to several different species, that follow the ants in the woods. On approaching, a dense body of the ants, three or four yards wide, and so numerous as to blacken the ground, would be seen moving rapidly in one direction, examining every cranny and underneath every fallen leaf. On the flanks and in advance of the main body smaller columns would be pushed out. These smaller columns would generally first flush the cockroaches, grasshoppers, and spiders. The pursued insects would rapidly make off, but many in their confusion and terror would bound right into the midst of the main body of ants."

Bates has the following regarding the Ecitons (page 354):

"One or other of them is sure to be met with in a woodland ramble, and it is to them, probably, that the stories we read in books on South America apply of ants clearing houses of vermin, although I heard of no instance of their entering houses, their ravages being confined to the thickest parts of the forest.

"When the pedestrian falls in with a train of these ants, the first signal given him is a twittering and restless movement of small flocks of plain-colored birds (ant thrushes) in the jungle. If this be disregarded until he advances a few steps farther, he is sure to fall into trouble, and find himself suddenly attacked by numbers of the ferocious little creatures. They swarm up his legs with incredible rapidity, each one driving its pincer-like jaws into his skin, and with the purchase thus obtained, doubling in its tail, and stinging with all its might. There is no course left but to run for it; if he is accompanied by natives, they will be sure to give the alarm, crying, 'Tauóca!' and scampering at full speed to the other end of the column of ants. The tenacious insects who have secured themselves to his legs then have to be plucked off one by one, a task which is generally not accomplished without pulling them in twain, and leaving heads and jaws sticking in the wounds.

"The errand of the vast ant armies is plunder, as in the case of Eciton legions; but from their moving always amongst dense thickets, their proceedings are not so easy to observe as in that species. Wherever they move, the whole animal world is set in commotion, and every creature tries to get out of their way. But it is especially the various tribes of wingless insects that have cause for fear, such as heavy-bodied spiders, ants of other species, maggots, caterpillars, larvæ of cockroaches, and so forth, all of which live under fallen leaves or in decaying wood. The Ecitons do not mount very high on trees, and therefore the nestlings of birds are not much incommoded by them.

"The armies never march far on a beaten path, but seem to prefer the entangled thickets, where it is seldom possible to follow them. I have traced an army sometimes for half a mile or more, but was never able to find one that had finished its day's course and returned to its hive. Indeed, I never met with a hive; whenever the Ecitons were seen they were always on the march" (p. 355).

ANTS AS FOOD

In the Amazon region some of the ants are even used by the Indians for food.

"I have many times seen Indians eat the *saúba* ant (called *bacháco* in Venezuela). The large kinds only are eaten, and at those times when the bachacos pour from their holes in great numbers (probably sending forth colonies after the manner of bees), if it be near any pueblo, all the unoccupied Indians in the place turn out to collect them. The head and thorax are the parts eaten, the abdomen being nipped off (at San Carlos I constantly see them eaten entire), and it is eaten uncooked. The taste to me is strong, fiery, and disagreeable, but those who have eaten the bacháco fried in turtle oil tell me it is quite palatable."[23]

In the more thickly settled parts of Brazil the custom of eating these ants is either not practiced nowadays, or, if it is, it is not generally known.

[23] Richard Spruce: Notes of a botanist on the Amazon and Andes, vol. 1, p. 484. London, 1908.

In the early history of the country, however, when the native Indians were much more abundant than they are now, the custom appears to have been common. Gabriel Soares de Souza, after living 16 years in Bahia, wrote as follows in 1587:[24]

"There are in this same country other ants which the Indians call *içans*, and which have bodies the size and color of an Alicante raisin . . . which live on the leaves of trees and worms and other small animals they find on the ground; these ants the Indians eat roasted over the fire, and they are greatly enjoyed; and some white men who live amongst them and the half-breeds regard them as good food, and boast of it as being very savory; . . . and when roasted they are white on the inside."

Orton[25] says the *saúbas* "are eaten by the Rio Negro Indians, and esteemed a luxury, while the Tapajos tribes use them to season their mandioca sauce."

STRUCTURES ABOVE GROUND

Origin of the structures.—The word "nests" frequently applied to the superficial structures of ants should not be understood to mean nests in the ordinary signification of the word. These structures sometimes contain the queens, eggs, and larvæ, but at other times these are kept in excavations below the surface.

The mounds made by the true ants all begin as small funnel-shaped ridges around the excavations started by individual females. The large mounds are the results of the work of many generations and of a vast number of individuals.

Without going into any detailed description of the habits of the ants, it is worth while to give, for those unfamiliar with their habits, a general idea of the methods followed by these ants in establishing new colonies and in increasing them. When the swarming or mating season of the *saúba* ants comes, the young females leave their homes and fly away. They seem to fly about very much at random—at least, I have rarely seen them going in any particular direction—and when they have been seen going together it was apparently due to the direction of the wind or the position of the sun at the time, rather than to any definite purpose on their part.

When the female alights after a flight of only a few minutes, she breaks off her wings and at once falls to work at excavating a burrow. All kinds of places are selected for these burrows. It does not appear that the selection is deliberate, but it seems to be determined by the acci-

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[24] Gabriel Soares de Souza: Tratado descriptivo do Brazil em 1587. Revist. Inst. Hist. do Brazil, vol. xiv, pp. 273-274. Rio de Janeiro, 1851.

[25] James Orton: The Andes and the Amazon, 3d ed., p. 301. New York, 1876.

dent of alighting from an aimless flight. Judging from the large number of individual females I have frequently seen in the air and on the ground at one time, the great majority of these young colonies must fail to survive. Often I have seen the young females so abundant that there must have been an individual to every square meter of land surface over areas of many hundreds of acres.

In some places where the new arrivals alight the mounds are already so thick that there is little or no room for new colonies, and it is probable that some of these young females must either be adopted into the old colonies or they are killed or die.[26]

It is evident from the nature of the case that where such a large number of new colonies is started most of them must perish from mere overcrowding, if for no other reason.

The excavation first made by a young female is small and simple, and the earth taken from it is heaped about the opening without any apparent order. Doctor Huber, in the paper just cited, states that at Para, in a colony started by a single female, the first workers appear at the end of 40 days. Shortly thereafter the queen, or founder of the colony, ceases to be an active worker, and all subsequent excavating is done by the constantly increasing number of workers. As the colonies increase in numbers more underground room is required, and the amount of earth excavated and carried to the surface increases proportionately. This earth is brought to the surface in the form of small pellets in the jaws of the workers, and are thrown down apparently without any other object than to be rid of them. Sometimes they are heaped up in funnel-shaped pits; sometimes they are thrown out on the downhill side of the opening. At first these bits of earth form heaps of loose, incoherent material, but in time, and with rain and sunshine, it packs down until it is often as hard as an unbaked brick. As long as the colony is active and growing, additions are constantly being made to these accumulations, and these additions may be at any point over the sides or at the top. Passageways are either kept open through these heaps of earth or they are reexcavated. This is demonstrated by digging into the mounds; but it is evident without opening them, from the fact that the fresh material is brought out and spread over any and all parts of the surface.

Size of the mounds.—It might be inferred that there would be prectically no limit to the size of the mounds built in this fashion, and I am not sure that there are any limits save those which may be imposed by

[26] Just how new colonies of saubas can be established by a single female is described by Dr. J. Huber, in Biologisches Centralblatt, vol. xxv, pp. 606-618, 624-635, and in the Boletim do Museu Goeldi, vol. v, pp. 223-241. Pará, 1907-8. Also in the Annual Report of the Smithsonian Institution for 1906, pp. 355-367.

certain physical conditions, such as the amount and distribution of the rains, the character of the soil, the area over which the necessary plants or food can be obtained, etcetera. Of course, the mounds are of different sizes according to their ages; but considering only the largest and oldest ones made by a single species, and found in various different localities, it is noteworthy that there is a great difference in the sizes of the largest of them. Just what determines this variation I can not say positively, but the influences referred to above—that is, rainfall, character of soil, and vegetation—naturally suggest themselves as possible influences.

Bates has the following in regard to the mounds made by the *saúbas* in the vicinity of Para:[27]

"In our first walks we were puzzled to account for large mounds of earth, of a different colour from the surrounding soil, which were thrown up in the plantations and woods. Some of them were very extensive, being forty yards in circumference, but not more than two feet in height. We soon ascertained that these were the work of the saúbas, being the outworks, or domes, which overlie and protect the entrances to their vest subterranean galleries. On close examination, I found the earth of which they are composed to consist of very minute granules, agglomerated without cement, and forming many rows of little ridges and turrets. The difference in colour from the superficial soil of the vicinity is owing to their being formed of the undersoil, brought up from a considerable depth. It is very rarely that the ants are seen at work on these mounds; the entrances seem to be generally closed; only now and then, when some particular work is going on, are the galleries opened."

Nowhere do I remember to have seen more or larger ant-hills than along Rio Utinga, in the diamond regions of the interior of the State of Bahia. From the town Riachão, down the river to the village of Pegas, the examples are big and abundant. In a few places they are so close together that, big and little, they appear to cover half of the ground. My notes, written on the spot, say "more than half of the ground." Such places, however, are exceptional. The distribution is always more or less irregular—bunched apparently on account of characteristics of soil or drainage, or for some other reason that does not appear. In some areas of from 10 to 20 acres the ant-hills occupy from a fifth to a third of the ground, while over larger tracts they take up from one-eighth to a seventh of the ground. In height the mounds are often as much as 5 meters high, with bases 15 or 16 meters in diameter. In the forests these mounds are generally overgrown with young trees. On many of the big mounds I have seen trees more than 30 centimeters in diameter. At the village of Antonio José the people have planted pineapples upon the mounds.

[27] Naturalist on the River Amazons, 4th ed., p. 10. London, 1875.

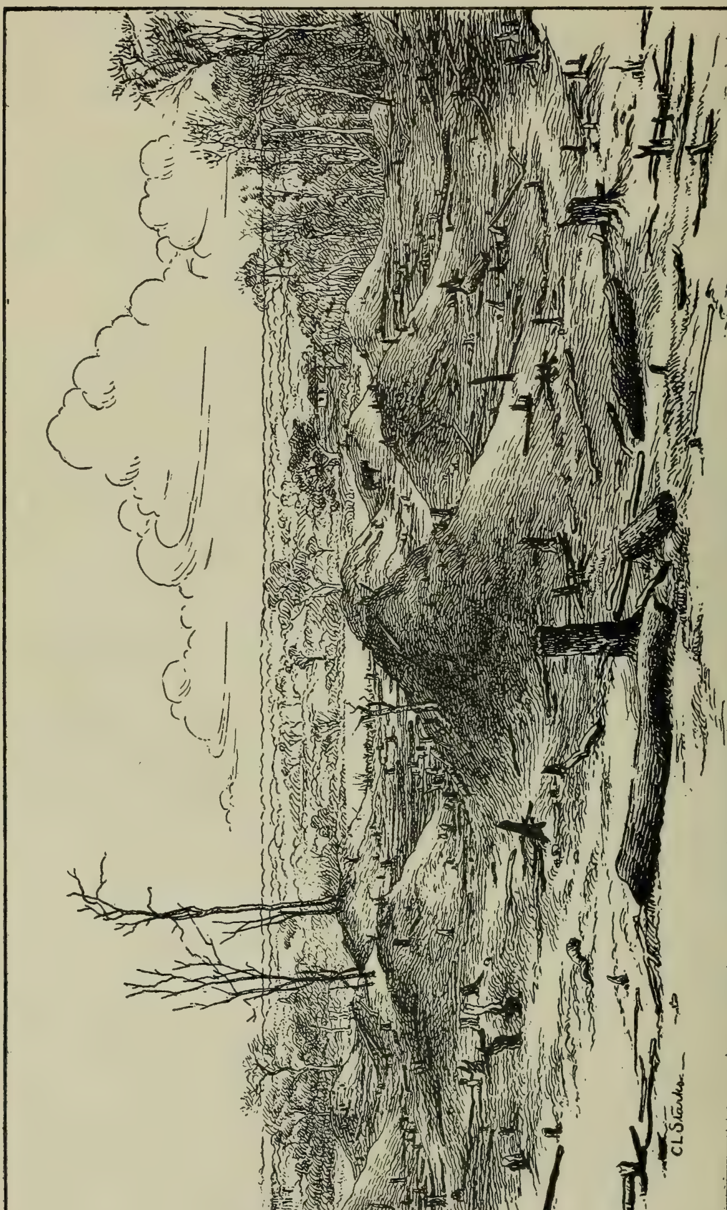

FIGURE 1.—*Ant-hills on Rio Utinga, near the Village of Pegas, State of Bahia*

From a photograph by R. Crandall, 1907

At fazenda Bello Horizonte, about 18 kilometers north of the village of Pegas, the ant-hills are so large and stand so thickly upon the ground that they form one of the most striking illustrations I have ever seen of the work of these insects. An area of some 30 acres or more is there covered with mounds resembling haycocks. They probably average 2 meters in height and a diameter of 4 or 5 meters at the base.

At a place called Ponte Nova, on Rio Utinga, 8 kilometers north of the village of Pegas, the ant-hills are a remarkable feature of the landscape. To the east and northeast of the Protestant college the mounds

FIGURE 2.—*Ant-hill (Formiga de mandioca) near Mundo Novo, State of Bahia, Brazil*

From a photograph by R. Crandall, 1907

cover the old fields. One of the accompanying photographs (figure 2, plate 35) and figure 1 were made in this region.

In the region south of Morro do Chapeo, in the State of Bahia, they are equally large on the clayey soils derived from the Caboclo shales.

The accompanying illustrations were made from photographs taken near Mundo Novo and Ventura, in that area.

Farther east in the State of Bahia, in the vicinity of Serrinha, a station on the São Francisco Railway, the ant-hills are large and abundant.

Six kilometers north of the station one was found by measurement to be 1.8 meters high and 4.5 + meters wide at the base. This mound was not regarded by the people of the locality as anything unusual.

To the east of Serrinha several mounds were observed with a height of 3 meters and a diameter at the base of 10 meters. These mounds, therefore, contain each 78.5 cubic meters of earth.

At and about Catuny, a station on the São Francisco Railway, the ant mounds are notably abundant, and many of them have a height of 1.5 meters.

FIGURE 3.—*Ant-hills made by the "Formiga de mandioca," near Ventura, State of Bahia, Brazil*

From a photograph by R. Crandall, 1907

Along the western half of the Bahia and Minas Railway, that starts from the coast near Caravellas, in the southern part of the State of Bahia, and runs west 376 kilometers into the State of Minas Geraes, ant-hills are big and abundant. The newer ones are steeply conical, but with age they become more or less rounded and flattened. In the vicinity of Urucú Station (kil. 226) the mounds are so thick and so close together that the country looks like a field of gigantic potato hills.

In some places they stand so close that their bases touch each other, though such cases appear to be rather exceptional. The mounds in this part of Minas and Bahia that appear to have reached their full development range from 1 to $4\frac{1}{2}$ meters in height and from 3 to 10 meters in diameter at the base. The biggest of these mounds—that is, one 4.5 meters high and 10 meters in diameter—contains approximately 117 cubic meters of earth.

Mention has already been made of the abundance and size of the mounds in some parts of the Rio Utinga region, in the interior of Bahia. At one place in this region, where the forests had been cleared away so that the mounds were clearly visible, I selected a spot where they were strikingly abundant, and measuring a space 100 by 100 meters, as nearly as it could be done by pacing, counted the mounds within the area and estimated their heights and diameters at the base.

The slopes of these mounds vary from less than 30 degrees up to 47 degrees, and on some parts of them there are even perpendicular places. It was thought that 38 degrees was a fair average for the ones in this particular area.

The figures obtained are given in the table below:

Table of Areas and cubical Contents of Mounds of different Sizes within an Area of 10,000 square Meters.

(All measurements are in meters.)

Number of mounds.	Diameter of base.	Area of each in square meters.	Total area in square meters.	Height.	Cubical contents.	Total contents in cubic meters.
1	15	176.71	176.71	4.5	265	265
2	11	95.03	190.06	4.2	133	266
6	10	78.54	471.24	3.9	102	612
8	8	50.26	402.08	3.1	51	408
12	7	38.48	460.76	2.9	37	444
5	6	28.27	141.35	2.3	21	105
4	5	19.63	78.52	2.0	13	52
7	4	12.56	87.92	1.7	7	49
8	3	7.06	56.48	1.2	3	24
Totals, 53	....	....	2,064.82	....	....	2,225

This estimate makes the area actually covered by the mounds close to one-fifth of the total area under consideration. My notes show that within areas of a few acres the ground covered by the mounds is sometimes as high as one-half of the total area. The cubical contents of the mounds, if evenly distributed over the entire 10,000 square meters, would have a thickness of 22.25 centimeters.

Although the mounds within the area here considered were large, they were not the biggest I have seen, nor do they average as large as can be found. The largest ones measured were on the upper drainage of Rio Utinga; several of these were found to be 5 meters high and 16 and 17 meters in diameter at the base, and each contained, therefore, about 340 cubic meters of earth. There were no other mounds closer to these than 10 or 15 meters.

M. Gounelle, a French entomologist, has calculated from a photograph the size of some of the Bahia mounds. Following is a translation of a part of his article. The mounds mentioned by him are near Condeuba, which is in the southern part of the State:[28]

"A photograph shown to the Society makes it possible for one to appreciate the enormous amount of work done by certain ants, and to measure fairly well the volume of the materials moved by them in digging their galleries. This photograph, taken in the vicinity of the little city of Condeuba, in the southern part of the State of Bahia, shows a clearing in which appear five conical nests of an ant, probably *Oecodoma cephalotes* Latreille.[29] The five cones have about the same dimensions. One notes in the foreground that the scale is one centimetre to the metre, as is readily seen by comparison with the man standing on top of the mound. Its diameter is 16 metres and its height is 4.5 metres, which by a simple calculation gives 301 cubic metres for its volume and 1,500 cubic metres for the total volume of the five mounds. The clearing has a surface of about one hectare, so that the earth of the five mounds, if spread evenly all over it, would have a thickness of 15 centimetres. . . . It should be added that the building of ant-hills of this size within a limited area is not an isolated case. The traveller in these regions meets with them everywhere, and that, too, over an enormous extent of country."

The reader should be reminded just here that this sort of thing is not to be seen in all parts of the country, by any manner of means. So far as my own observations go, ant mounds are unusually large and unusually abundant in this particular part of Brazil.

Age of the mounds.—The amount of work done by these ants in a region where they seem to be favorably located is fairly well shown in the preceding table. Trustworthy data for calculating the time required to build a mound of a given size or to do any given amount of work is lacking. Necessarily the time must vary with the size of the colonies, other things being equal. The colonies, however, appear to have their ups and downs, for while some of them increase in numbers and continue to add to the mounds for long periods, others appear to be less active, while still others disappear, whether by migrating or through the death or captivity of the members is not certainly known at present. It is interesting to note that the Brazilians generally regard the size of the ant-hill as

[28] E. Gounelle: Transport de terres effectué par des fourmis au Brésil. Annales de la Société Entomologique de France, 7me sér., no. 6, pp. 332-333. Paris, 1896.

[29] This is the name of the so-called *sauba*. J. C. B.

directly related to the age of the colony. At Serrinha, on the São Francisco Railway, I was told that mounds about 2 meters high and having a base of about 5 meters were probably as much as a hundred years old. This was an expression of views based simply upon a general impression and not upon records.

M. Gounelle[30] says in regard to the age of ant-hills:

"The age of these ant-hills is rather difficult to determine; however, the curate of the city mentioned above (Condeuba, Bahia) has assured me that three nests like those in the photograph, located at the entrance to the cemetery, were not more than one metre high when he went to that country, about sixty years ago. Taking a hundred years as an average for the building of these gigantic ant-hills, it does not seem rash to suppose that in these regions the soil must have been worked over by the ants to a certain depth several times in the course of geologic periods."

UNDERGROUND WORK

So far as I can learn, there has never been any careful examination or study of the character, extent, and uses of the underground excavations made by ants in the tropics. What is known about them has been learned accidentally, and our knowledge of the passages is, therefore, fragmentary. I have frequently dug into the mounds, but always without the time necessary for satisfactory results. The most I have been able to make out in these hasty explorations is that the superficial mounds are penetrated in every direction with passageways. The large mounds were in no case opened down to the original surface of the ground; but when small mounds were opened they were found to connect through small tunnels with the underground excavations.

A pit started by the removal of a large ant-hill east of Timbo, in the interior of Bahia, and continued to a depth of about 4 meters, showed the arrangement of the underground tunnels better than I have seen it elsewhere. The section did not pass through the main shaft or tunnel that connected the ant-hill with the subterranean excavations, but a little to one side of it. The upper layer of the earth, to a depth of half a meter, was undisturbed; then there was one tunnel with a flat floor, about 20 to 25 centimeters across, and having a low arched roof; below this, at a distance of about 25 centimeters, were two tunnels at the same level and of about the same size and shape; below these, at a further depth of about 25 centimeters, were three similar openings. This arrangement continued to a depth of nearly two meters, the tunnels being more numerous always at the lower levels. The tunnels at the lowest

[30] E. Gounelle: Transport de terres effectué par des fourmis au Brésil. Bull. Soc. Entomologique de France. 7me sér., no. 6, p. 332. Paris, 1896.

level did not form a complete row, but the work seemed to have been commenced at the outside.

This same arrangement of the tunnels has been seen frequently in railway cuts and ditches, but nowhere else have I seen so many levels or such a clearly defined plan in the placing of the excavations.

In some other cases noted the number of tunnels connecting the above-ground mounds with the underground galleries seemed to vary with the size of the mounds—that is, the more ground the mound covered, the more passageways there seemed to be to connect with the galleries beneath.

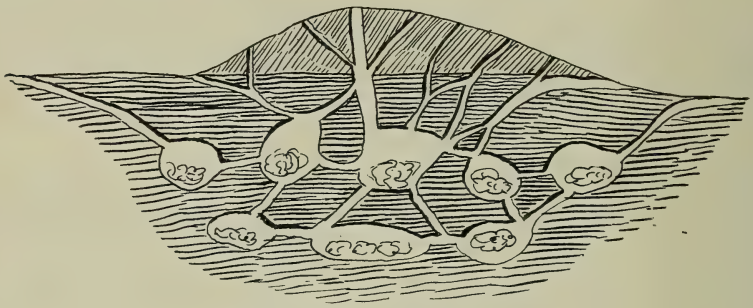

FIGURE 4.—*Nest of leaf-cutting Ant*
After Belt. "The Naturalist in Nicaragua," p. 80

Bates gives the following regarding the *saúbas*:[31]

"The entrances are small and numerous; in the large hillocks it would require a great amount of excavation to get at the main galleries; but I succeeded in removing portions of the dome in smaller hillocks, and then I found that the minor entrances converged, at the depth of about two feet, to one broad, elaborately worked gallery, or mine, which was four or five inches in diameter."

The section through the burrows given by Belt is reproduced in figure 4. This section, however, is diagrammatic, and does not claim to show the great extent of the galleries. Belt tells, however, of galleries 1.5 meters in depth (page 76). The best evidence I have been able to gather in regard to the depth to which the ants penetrate has been obtained in cuts along railways and canals, and in deep ditches often dug to serve as fences. On Rio do Peixe, near Serro, in the State of Minas Geraes, I found the galleries as deep as 2.5 meters at several places along a canal under construction. Most of them, however, were only about 1.5 meters below the surface at the deepest points exposed. At Bomfim, on the

[31] H. W. Bates: The Naturalist on the Amazons.

Bahia and São Francisco Railway, I found the burrows exposed in a deep ditch at a depth of 2.1 meters.

Sampaio, a Brazilian entomologist who has given much attention to the *saúba* ants, shows one burrow as much as 3.5 meters below the surface.[32]

In the State of São Paulo, Brazil, the coffee planters have among their employees men whose business it is to fight the *saúbas*. These ant-killers, in the course of their operations against the ants, are said to open out sometimes their underground excavations to a depth of 3.6 meters.

Dr. Jaoquim Lustosa, a Brazilian mining engineer of Lafayette, State of Minas Geraes, Brazil, writes me (June 16, 1909) as follows in regard to the depth to which ants burrow in Minas: "Competent persons assure me that the true ants burrow to a depth of 10 metres or more, and that they exhibit a strange and remarkable intelligence, and that they even cross wide and deep streams by means of tunnels so deep as to avoid the infiltration of the water."

The length of the tunnels has often been demonstrated by forcing smoke through them. I have myself seen fumes blown into one opening and issuing from others as much as 300 meters away. Mr. Charles J. Dulley, a civil engineer of São Paulo, informs me that he has seen fumes driven into the chief nucleus of a colony of *saúbas*, and issuing 183 meters away.

The following statement is given in Mrs. Agassiz's book:[33]

The *saúbas*

"make houses by excavating, and sometimes undermine a hill so extensively with their long galleries that when a fire is lighted at one of the entrances to exterminate them, the smoke issues at numerous openings, distant perhaps a quarter of a mile from each other, showing in how many directions they have tunneled out the hill, and that their winding passages communicate with each other throughout."

On the authority of Rev. H. Clark, Bates says[34] that ants

"excavated a tunnel under the bed of the River Parahyba, at a place where it is as broad as the Thames at London Bridge. At the Magoary rice mills, near Pará, these ants once pierced the embankment of a large reservoir; the great body of water which it contained escaped before the damage could be repaired. In the Botanic Gardens at Pará, an enterprising French gardener tried all he could think of to extirpate the saúba. With this object he made fires over

[32] A. G. de Azevedo Sampaio: Sauva ou Manhu-uára, pp. 22, 52, 64. Sao Paulo, 1894.
[33] Prof. and Mrs. Louis Agassiz: A journey in Brazil, p. 105. Boston, 1868.
[34] H. W. Bates: Naturalist on the Amazons, 4th ed., pp. 9-15. London, 1875.

some of the main entrances to their colonies, and blew the fumes of sulphur down the galleries by means of bellows. I saw the smoke issue from a great number of outlets, one of which was 70 yards distant from the place where the bellows were used. This shows how extensively the underground galleries are ramified."

Another writer, Rev. J. C. Wood, tells of the *saúbas* having

"ruined a gold mine for a time, breaking into it with a tunnel some 80 yards in length and letting in a torrent of water, which broke down the machinery and washed away all the supports, so that the mine had to be dug afresh."[35]

The diameter of an underground passage varies from 1 or 2 centimeters up to 5 centimeters or more. They widen out and narrow down without any apparent reason, and those made by the *saúbas* that have been examined have here and there local enlargements that are commonly from 1 to 2 decimeters in height and from 1 to 3 decimeters in length. These chambers, when freshly opened, I have generally found filled, or partly filled, with loose, mouldy masses of dead leaves.

Belt describes the underground passages in Nicaragua as follows:[36]

"In our mining operations we also, on two occasions, carried our excavations from below up through very large formicariums, so that all their underground workings were exposed to observation. I found their nests below to consist of numerous rounded chambers, about as large as a man's head, connected together by tunneled passages leading from one chamber to another."

RELATIONS TO THE SOIL

The distribution of ant colonies as shown by their mounds suggests, if it does not prove beyond question, that the character of the soil has an important influence on the distribution of the ants themselves. In view of the habits of ants, it seems highly probable that at the time of leaving their nests the young females scatter over the surrounding region pretty much at random. When they alight, some of them find themselves in locations where ant colonies, on account of the character of the ground, can not possibly survive, and as these young females break off their wings as soon as they alight, they can not renew their flight and seek more favorable ground, but they must perish without having founded a new colony. And this must happen over and over again, with the final result that localities unfavorable for ants do not have ant colonies, while the favorable localities may have a superabundance of them. Favorable and

[35] Charles Waterton: Wanderings in South America. Explanatory Index, Rev. J. G. Wood, p. 47. London, 1882.

[36] The Naturalist in Nicaragua, p. 80.

unfavorable conditions are not always sharply defined, but merge into each other.

In some cases it is quite evident what constitute unfavorable conditions. Ground that is constantly wet or liable to inundation can not be occupied; hard, rocky surfaces, or even very thin soils, are not available; soils so sandy or friable that underground tunnels dug in them will not stand are evidently not available for the establishment of colonies.

Between soils most favorable and unfavorable ones there are all sorts of gradations, so that one is prepared, for this reason alone, to find the ant-hills bigger and more abundant in some places than in others. It is evident that it is all a question of adaptability, however, rather than a matter of choice on the part of the ants.

Just what kind of soil is most favorable for the ants I can not state positively. My general impression is that the mounds are most abundant on clayey soils, whether the clay comes directly from the decomposition of feldspathic rocks or from the disintegration of shales and slates.

This preference for the clayey soils is well shown at many places through the diamond-bearing highlands of the interior of Bahia, where the diamond-bearing quartzites, known as the Lavras series, are underlain by a thick series of shales called the Caboclo (or Paraguassú ?) series. The Lavras beds being quartzites, or sandstones, break down into a very sandy soil, while the Caboclo shales form a stiff, clayey soil, and as they are adjacent to each other the line of demarcation between the two soils is usually well defined. While traveling through that district in 1907, I was frequently able to locate myself geologically by the abundance or absence of the ant-hills. Not infrequently the line of parting between the two series was concealed by a thick soil and overgrown with forests, but the distribution of the mounds would often show the line of parting within 20 or 25 meters.

My former assistant, Mr. Roderic Crandall, who has traveled extensively in Bahia, Pernambuco, Piauhy, Minas, and Goyaz, writes, in reply to my inquiries, as follows regarding the preference of the ants for certain soils: "In Bahia the ants of all kinds show a preference for the Estancia and Caboclo shales; next to these the granites seem to have the biggest nests." (Private letter; Rio, June 23, 1909.)

I infer that the smaller number of the mounds on the sandy soil is due to the fact that during the rainy season water soaks through into the burrows, and the excavations do not stand up where the soil is wet.

Thinking it possible that the exposure of the mounds or of the ground on which they stand to the sun might influence location and distribution, an outlook has been kept with these questions in mind. It does not appear thus far that such exposure influences the location or size of the mounds, even in the southern part of Brazil, where the sun is on the north most or all of the year.

The White Ants, or Termites

GENERAL CHARACTERISTICS

The so-called white ants, or termites, belong to the *Isoptera*, and are therefore not ants at all. They are included in this paper solely on account of the geologic work done by them in the tropics, which bears a certain similarity to the geologic work of the true ants.

In Brazil the white ants are commonly known by the name of *cupim*. In their habits the white ants both resemble and differ from the true ants. They generally avoid the light, carrying on their work, even when it is above ground, in galleries which they construct as they go. Their nests are sometimes attached to tree trunks or rocks, but they are often built directly upon the ground. Not infrequently these nests are as large, or even larger, than the nests of the true ants, but they are very different in shape and character.

ABUNDANCE

Here, again, I am unable to give anything regarding the biology of the white ants.[37]

Dr. Fritz Muller, who lived for many years in southern Brazil, reports 15 or 16 species of termites in that part of the country, but not all of these live on or in the ground.

M. Jules Desneux, in his monograph on the Termitidæ, reports 45 species from Brazil and some 15 or more from other tropical parts of America.

White ants, like other animals, are not evenly distributed in the tropical parts of South America. They are so much less obtrusive and pugnacious, however, that they do not attract the attention as promptly as do the true ants.

Azara says he has seen these insects during the mating season filling the air for more than a mile.[38]

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[37] For the benefit of those who are interested in the biology of white ants I cite the following:

K. Escherich: Die Termiten oder weissen Ameisen. Eine Biologische Studie, vol. xii, p. 198. Leipsig, 1909.

Genera Insectorum publies par P. Wytsman. Fasc. 25, Isoptera, fam. Termitidæ par Jules Desneux. Bruxelles, 1904.

[38] Don Felix de Azara: Voyages dans l'Amérique Meridionale, t. i, p. 192. Paris, 1809.

The fact that the white ants live and work entirely under cover might naturally lead one to infer that they were much less abundant than the true ants. But nowhere have I found the ground as thickly covered with the termites' nests as with those of the true ants, a fact probably due to some extent to the methods by which the two kinds of insects procure their food supplies.

I have never been able to estimate the number of individuals in the old colonies, nor have I found such an estimate made by any one else. In the matter of numbers we are obliged to depend on general impressions gained from the abundance of the above-ground structures of the separate colonies and from certain of their habits. For example, it is stated that the queen of an allied species whose habits have been studied has "an egg-laying rate of 60 per minute, or something like 80,000 per day."[39]

Prince Maximilien, who traveled through the region between Rio and Bahia, says of their abundance: "One can get some idea of their prodigious numbers when he remembers the vast extent of the interior of Brazil, and of the number of the little animals that occupy these nests, when he reflects that one can not go 20 paces without meeting their mounds."[40]

This statement must be taken with certain allowances, for, as pointed out elsewhere, the nests are not everywhere equally abundant.

ANIMALS FEEDING ON TERMITES

As the white ants have no means of defense against their natural enemies, they are easily destroyed and are preyed on by many other insectivorous animals. Indeed, one of the impressive evidences of the great numbers of the white ants in South America is the existence there of certain large vertebrate burrowing animals that are said to feed almost exclusively upon the white ants.[41]

The great ant-eater, known in Brazil as the *tamanduá bandeira,* is said to live entirely on ants. Brazilians acquainted with the habits of the *tamanduá* tell me, however, that the ant-eater does not eat the *saúbas* or other biting or stinging ants, but that it lives chiefly and almost exclusively on the *cupim,* or so-called white ant. To give an idea of the size of the animal, I quote the following measurements of an ant-eater as given by Wells: Head, 16 inches; back, 4 feet; tail, 4 feet; total length, 9 feet 4 inches. He says it has no teeth.[42]

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[39] C. L. Marlatt: Circular 50, p. 3, 2d ser., Bureau of Entomology, U. S. Department of Agriculture. Washington, 1908.

[40] Maximilien, Prince de Wied-Neuwied: Voyage au Brésil, t. iii, p. 129. Paris, 1822.

[41] Holes often found in the mounds of the true ants show that some of these large ant-eating animals feed on the true ants also.

[42] J. W. Wells: Three thousand miles through Brazil, vol. ii, p. 141. London, 1886.

The existence of an animal as big as an ordinary dog, over 2 feet high at the shoulder, with its long, slender muzzle, its powerful forelegs and claws adapted to the excavation and exploration of ant-mounds, and its tongue nearly a yard in length, and living chiefly, if not entirely, upon white ants, is an important witness on the side of the abundance of termites in the region in which it lives. Bates reports four species of ant-eaters in the Amazonas region, two of which are large and two small ones (op. cit., 2d ed., p. 110), while Wallace says there are five species in tropical America, besides one extinct form.[43]

The armadillos, known in Brazil as *tatús*, are also ant-eaters. As Mr. Wallace points out,[44] the armadillos are highly characteristic of tropical South and Central America, and at the time of the publication of his famous work on the geographical distribution of animals they embraced 6 genera and 17 species, to say nothing of many extinct species found by Lund in the caves of Minas Geraes. Some of these armadillos are so large that a single individual will weigh as much as 75 pounds, or even more.

They live upon insects chiefly, and the white ants seem to be their favorite food. They enter the nests by digging openings at the base of the cones with their powerful fore feet.[45]

Gardner states that the white ants also form the principal food of the South American ostrich (*Rhea americana*), which is the largest bird in tropical America.[46]

In addition, there are large numbers of birds and reptiles, such as toads, frogs, lizards, and snakes, that habitually feed upon these insects. Azara says that almost all kinds of birds except the "milano" feed on them.[47]

The true ants are enemies of the white ants worthy of especial mention. The abundance of the ants and their pugnacious dispositions make them serious obstacles to the development of the termites' colonies, and they are probably their worst natural enemies. The termites have in their colonies forms that are known among biologists as soldiers, but so far as I have been able to determine from personal observations these soldiers do not attack the true ants, though they do take the place of sol-

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[43] A. R. Wallace: The geographical distribution of animals, vol. ii, p. 247. New York, 1876.

[44] Alfred R. Wallace: The geographical distribution of animals, vol. i, pp. 245-246. New York, 1876.

[45] The flesh of the *tatus* is very much prized for food, and this naturally leads to the hunting and killing of these animals, which should be protected.

[46] George Gardner: Travels in the interior of Brazil, p. 280. London, 1846.

[47] Don Felix de Azara: Voyages dans l'Amérique Meridionale, vol. i, p. 192. Paris, 1809.

diers in obstructing the passage of the ants into the termites' nests and galleries.

The result of the relations existing between the true ants and the termites is that the two kinds do not thrive together; at least I have never found the termites' nests where the *saúbas* or other true ants were notably abundant. Preyed on by the true ants and by animals of so many different kinds, and even by insects themselves, it occurs to one that their chances of survival in the midst of so many enemies must be very small. That survival appears to be due largely to their habit of living and working under the protection of their covered roadways, and to the fact that their roads are constructed of materials that are remarkably inconspicuous. Nothing could look more thoroughly abandoned and lifeless than the common run of white ants' nests and their covered passages; yet if one breaks through these coverings he will usually find them fairly swarming with life.

My general impression is that those white ants which build mounds of earth are especially abundant in the highlands of Minas Geraes and through the semi-arid portions of Sergipe, Bahia, Goyaz, Matto Grosso, and the interior of Ceará, Maranhão, and Piauhy. Mr. Crandall tells me that he finds them most common on the Diamantina plateau. (Letter of June 23, 1909.)

STRUCTURES ABOVE GROUND

General characteristics.—The nests of the white ants, or *cupim*, have no visible external openings. When a mound is new or is being added to, the outside of the new portion is so soft that it can be readily broken off with a stick; but with time the outside usually becomes as hard as a brick. This hard outside covers the entire mound, and is usually about 6 inches thick, but in the very big nests it is sometimes nearly or quite a foot thick. Inside of this hard, thick covering the materials are quite soft and brittle, and the partitions are sometimes almost as thin as paper, though thicker in the larger nests. Where the mound stands on the ground, the cavities of the upper portion connect through the perforated base with subterranean excavations.

Parts of the nests are made of the excrement of the inhabitants. I have often broken the nests or the covered roads of these insects in order to observe the workers repair them. In every case observed the repairs were made by building up a wall or covering of excrement or something of the kind. At least it is voided from the posterior part of the body in a plastic condition, and is smoothed down on the sides so that the later layers always override the earlier ones on both sides of the wall. An examination of their construction, however, shows that they are made partly of clay or the earth about the nest and partly of woody fiber. These two substances are variously mixed in structure, sometimes one being more abundant, sometimes the other. An examination of the

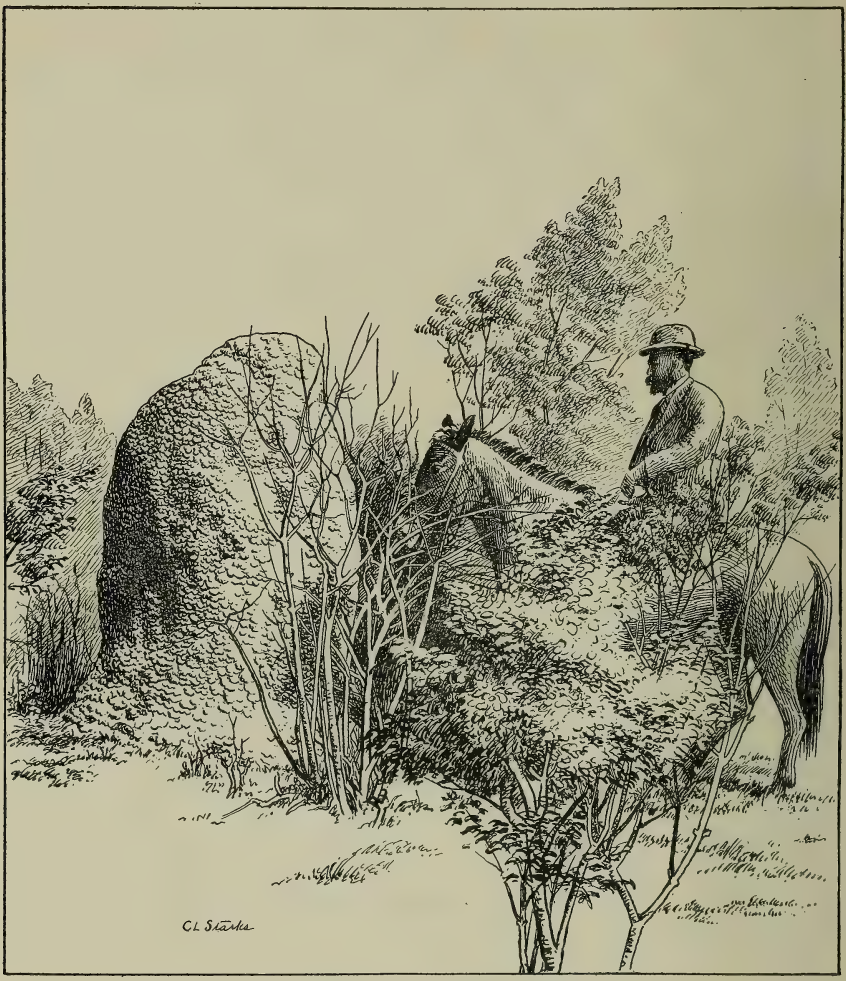

FIGURE 5.—*Above-ground Structure of White Ants*

Seven kilometers west of Queluz, between Piquiry and S. Gonçales, State of Minas Geraes. From a photograph by the author, August 4, 1907

materials of the outside part of the large and old nests, however, shows that this part of the nest at least contains fragments of quartz, sand grains, and such like rock fragments that could not possibly have passed through the bodies of the insects. The structure of some of the nest walls suggests that these walls are constructed partly of earth and rock fragments brought up from beneath the ground and built into the nests

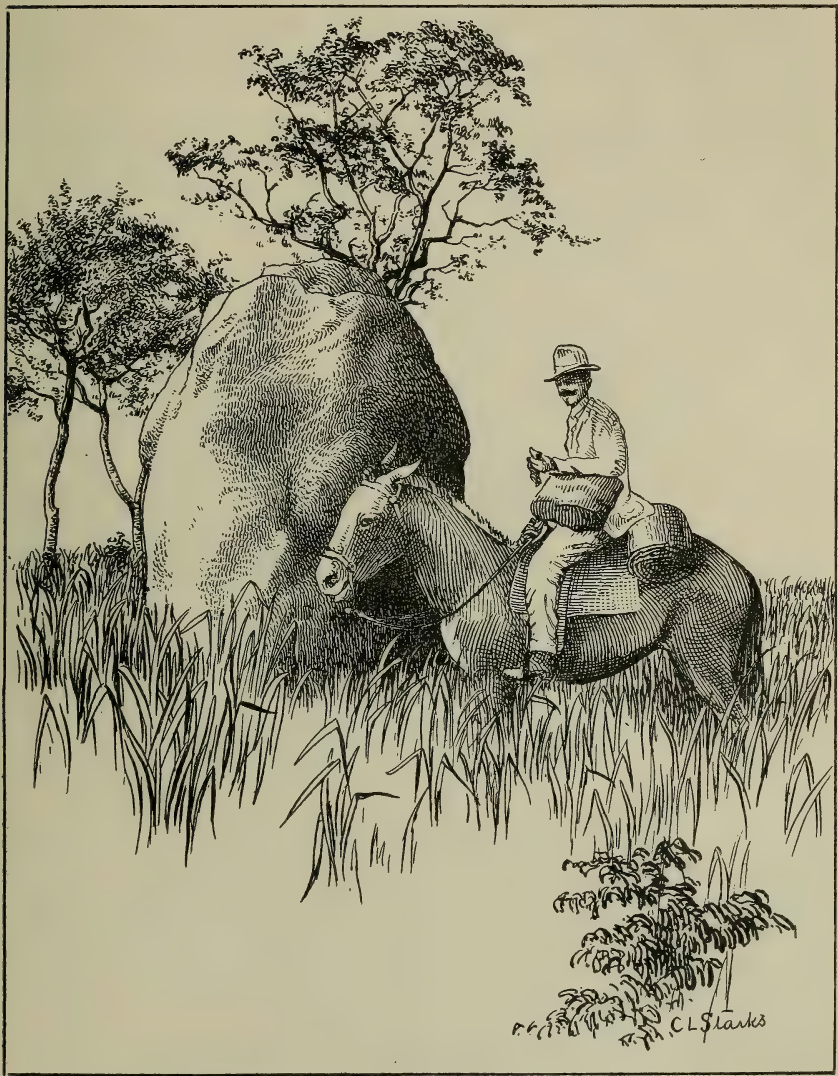

FIGURE 6.—*Mound of Termites or White Ants, State of Minas Geraes, Brazil*
From a photograph by R. Crandall, July, 1909

by cementing them together with excrement or some other adhesive substance.

The outer parts of the nests, when they stand on the ground, are, so far as my observations go, always made of earth cemented in a thick, hard wall. In the inner portions of the nest the partitions are thinner, and though they are made largely of an easy-spreading clay, they are often made partly, or at least overspread, with a dark, friable substance that has the appearance of being masticated wood, leaves, or other organic matter.

The openings through the mass of the nests are pretty uniform in size, being from 3 to 10 millimeters in diameter and averaging close to 5 or 6 millimeters. The openings within the nests sometimes have the appearance of being arranged in rude tiers; sometimes they are apparently haphazard labyrinths.

The external forms of the nests vary considerably, but unfortunately I do not know whether this variation is due to difference in the species of termites, to difference in the nature of the ground, or to other causes. As a rule the mounds are rudely domed, rounded or conical, and the method of adding to the outside gives them a bumpy, lumpy appearance, so that, as Burmeister suggests, they resemble gigantic Irish potatoes. In some localities they are mostly tall and slender. Most of the tall, slender forms observed have been in wet ground or on ground that is sometimes overflowed. For this reason it is inferred that these forms are due to the presence of water rather than to a different species of termites. In size they also vary greatly. I have seen them as much as 6 meters high and 8 meters in circumference, but these very large ones are exceptional.

In southern Minas, south of Barbacena, Dr. R. Walsh notes mounds of the white ants 10 or 12 feet high: "I rode close by several which were considerably higher than my head on horseback and 9 or 10 feet in circumference."[48]

Charles J. Dulley tells me that in the vicinity of Caximbu, in southern Minas, he has seen white ants' nests 4 meters high and nearly 2 meters in diameter at the base. Mr. H. E. Williams, assistant on the Geological Survey of Brazil, says that in the vicinity of Taubaté, in São Paulo, they are often 2.4 meters high, while about the city of São Paulo they usually are 1 meter and less in height.

Gardner says that many of the level tablelands of the interior of Piauhy, where the soil is red clay, the mounds of white ants are abundant and often 6 or 8 feet high.[49]

[48] Rev. R. Walsh: Notices of Brazil in 1828 and 1829, vol. ii, p. 50. Boston, 1831.
[49] George Gardner: Travels in the interior of Brazil, p. 280. London, 1846.

In the valley of Rio Sapão, in northwest Bahia, Wells notes great numbers of white ants' nests from 4 to 6 feet high.[50]

At and about Asuncion, in Paraguay, I found the nests very abundant on the clayey soils, and many of them as much as 3 meters high.

The outer portion of the nest being thick, hard, and compact, and the inside being friable and easily removed, it is a custom in the interior of Brazil and Paraguay to scoop out the inside of white ants' nests and to use them for ovens. The door is cut near the base of the cone, and the inside parts removed through it.

The accompanying illustrations will probably give a better idea of the sizes and shapes of the nests than verbal descriptions.

FIGURE 7.—*White Ants' Nest. built of Earth, in the State of Minas Geraes*

From a photograph by R. Crandall, July, 1909

I add short extracts concerning these nests taken from other writers.

The following is translated from Auguste de Saint-Hilaire:[51]

"In the vicinity of Parahyba we saw along the side of the road the nests of the termites, or white ants; further on we saw nothing of them, but near Pinho Velho, and especially near the Mantiqueira, we found large numbers of them. . . . The nests of the species common to the vicinity of Mantiqueira are made of a much masticated clayey earth. They are nearly cylindrical,

[50] J. W. Wells: He says that in that part of Brazil the mounds are often occupied by bees. Three thousand miles through Brazil, vol. ii, p. 127. London, 1886.

[51] Voyage dans les provinces de Rio de Janeiro et de Minas Geraes, vol. i, p. 108. Paris, 1830.

rounded at the top, and look like mile stones. Most of them are two or three feet high, but some of them are as much as five or six feet high, and I saw one that must have been twenty feet high and about as big round the middle where it was enlarged. The outside is covered with a crust as thick as a finger length, and no openings appear in it. The insides of some of these nests that have been overturned showed a series of black horizontal floors (planchers), one above another, close together, and pierced by round holes.

"The termites do not build their nests all at once. They enlarge them in proportion as the population of a colony increases, and the new parts are readily distinguished by the earth freshly laid on."

Sir Woodbine Parish speaks of "Corrientes and Paraguay, where whole plains are covered with their dome-like and conical edifices, rising 5 and 6 feet and more in height."[52]

FIGURE 8.—*White Ants' Nest of Earth in Matto Grosso, on the Plains of the Upper Paraguay*

Sketch by J. C. Branner

In the region about the headwaters of the Paraguay the nests of the white ants are extremely abundant in favorable localities, and the forms of the nests are different from those noted in other parts of tropical America. The tall and very slender forms are especially noticeable in the low, flat prairie lands south of Cuiaba. (See figure 8.) These slender forms are known in that part of Brazil by the Indian name of *tacurú*.

Dr. João Severiano da Fonseca has the following in regard to ants in the vicinity of the city of Matto Grosso:[53]

[52] Sir Woodbine Parish: Buenos Ayres and the provinces of the Rio de la Plata, 2d ed., p. 252. London, 1852.

[53] Viagem ao redor do Brazil, vol. 1, p. 352. Rio, 1881.

"The ants and the various kinds of *cupim* own the country. It is noteworthy that while their hives, or houses, vary in form according to the locality, they retain a certain uniformity of construction, having one shape here, another one there, and a different one somewhere else. I am unable to determine whether these differences depend on the soil and the materials of which they are constructed or upon the difference in the species of the constructors. It is certain, though, that in the vicinity of Cambara the country is covered with cylindrical columns called *tacurús* by the Indians. These are sometimes two metres high, and resemble the marks or columns known as stone friars. In some places, as below Corixa, on the Lixal and Burgres plateaus, they look like miniature castles half a metre high, with loopholes, gates, towers, and terraces. In other localities, such as Palma Real and Petas, they are lower, but thicker, sometimes isolated, and sometimes built against trees, but always very hard and made with a kind of bituminous cement that is impermeable to water."

Dr. Henry Drummond has the following on the white ants in tropical Africa:[54]

"The material excavated from these underground galleries and from the succession of domed chambers—used as nurseries or granaries—to which they lead, has to be thrown out upon the surface. And it is from these materials that the huge ant-hills are reared which form so distinctive a feature of the African landscape. These heaps and mounds are so conspicuous that they may be seen for miles, and so numerous are they and so useful as cover to the sportsman that without them in certain districts hunting would be impossible. The first things, indeed, to strike the traveller in entering the interior are the mounds of the white ant, now dotting the plain in groups like a small cemetery, now rising into mounds, singly or in clusters, each thirty or forty feet in diameter and ten or fifteen in height; or, again, standing out against the sky like obelisks, their bare sides carved and fluted into all sorts of fantastic shapes (see figure 9). In India these ant-heaps seldom attain a height of more than a couple of feet, but in Central Africa they form veritable hills, and contain many tons of earth. The brick houses of the Scotch mission station at Lake Nyassa have all been built out of a single ants' nest, and the quarry from which the material has been derived forms a pit beside the settlement some dozen feet in depth. A supply of bricks as large again could probably still be taken from this convenient depot, and the missionaries on Lake Tanganyika and onwards to Victoria Nyanza have been similarly indebted to the labors of the termites. In South Africa the Zulus and Kaffirs pave all their huts with white-ant earth, and during the Boer war our troops in Prætoria, by scooping out the interior from the smaller beehive-shaped ant-heaps and covering the top with clay, constantly used them as ovens. These ant-heaps may be said to abound over the whole interior of Africa, and there are several distinct species. The most peculiar as well as the most ornate is a small variety from one to two feet in height, which occurs in myriads along the shores of Lake Tanganyika. It is built in symmetrical tiers, and resembles a pile of small rounded hats, one above another, the rims depending like

[54] Henry Drummond: Tropical Africa, pp. 89-90. New York, 1891.

eaves, and sheltering the body of the hill from rain. To estimate the amount of earth per acre raised from the water-line of the subsoil by white ants

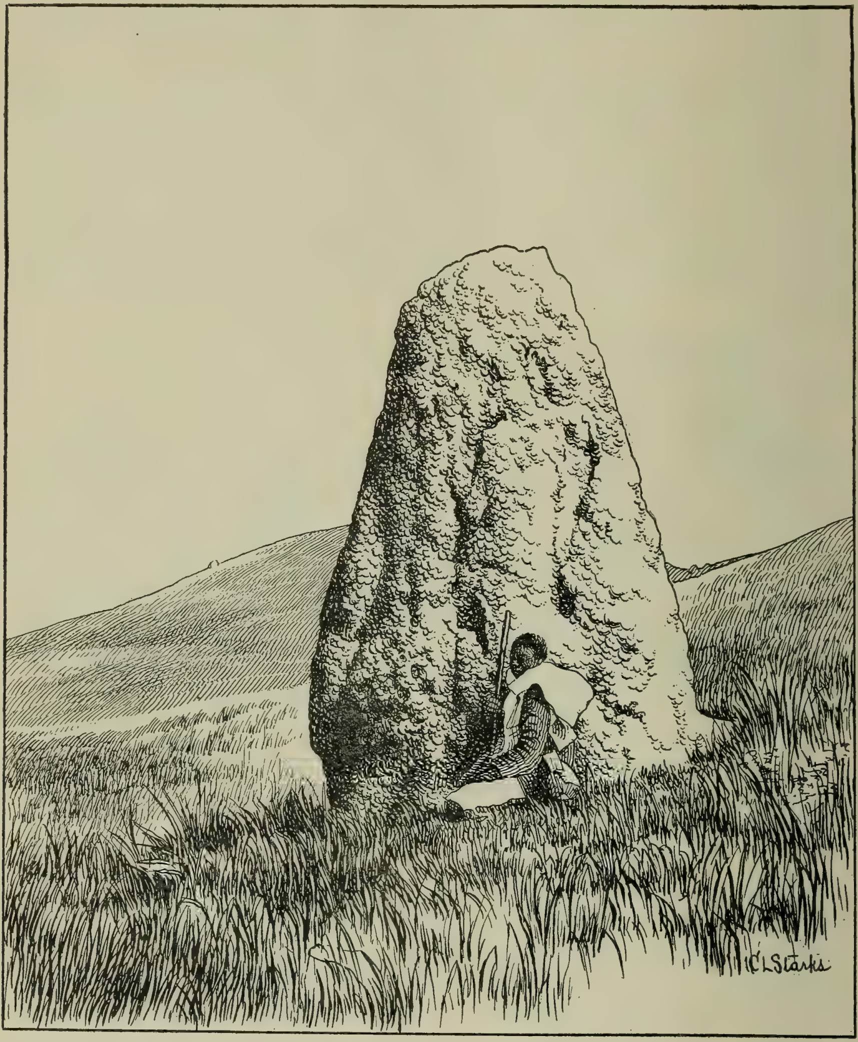

FIGURE 9.—*Mound of White Ants in the laterite Region of Africa*

Redrawn from "Il Ruwenzori," parte scientifica, volume ii. Prof. Alessandro Roceati. Petrografia e mineralogia. Milano, 1909, plate I, figure 1

would not in some districts be an impossible task, and it would be found, probably, that the quantity at least equalled that manipulated annually in temperate regions by the earth-worm.

"These mounds, however, are more than mere waste-heaps. Like the corresponding region underground, they are built into a meshwork of tunnels, galleries, and chambers, where the social interests of the community are attended to."

Age of the mounds.—The method of building the mounds and the habits of the termites, so far as I am acquainted with them, lead to the conclusion that the size of a mound is determined by its age and by the size of the colony building it. Just how long it requires to build the large mounds I have but little means of judging. One frequently sees nests built on houses and fences, and in these cases it has been possible to determine the maximum ages of these particular nests. These cases, however, afford only a suggestion. The oldest nests I have seen, and of which I could get an idea of their ages, were not more than 50 years old, and the biggest of them contained a little less than 1 cubic meter of earth, the estimate being made without reference to the cavities within the mass.

It is evident that the size and age in one of these cases may or may not help one to determine the time occupied in the construction of one of the very large nests figured in this paper, for the rates of building may have been very different.

UNDERGROUND STRUCTURES

The above-ground structures of the white ants connect with underground passageways, but wherever I have seen these passageways opened they appear to have been excavated and then to have been filled with smaller chambers made of materials like that used to make the chambers of the mounds above ground. An examination of the thin chamber walls found in some of the underground excavations shows that they have been constructed of soft, plastic materials so piled up that each later addition overlaps the preceding one on both sides of the wall. The materials are partly of reddish clay like that of the ground in which the nest is made, and partly of a dark brown substance that I take to be organic matter—probably masticated plants.

I have never seen the excavations made by the white ants more than a meter and a half below the surface, but I have heard of them being found considerably deeper. My friend, Dr. Joaquim Lustosa, of Lafayette, State of Minas Geraes, writes me on this subject: "As for the depth to which they penetrate the ground, it is my impression that it is but little more than 3 metres."

RELATION OF NESTS TO THE SOIL

The white ants do not seem to be so dependent on the character of the soil as do the true ants. This is probably due to the fact that when the true ants excavate their tunnels in the earth they depend on the character of the ground and the form of the excavations to support the structures. The white ants, on the other hand, depend partly on the nature of the soil, but partly on their method of cementing the materials of which their nests are made.

The preference, however, of the termites for certain soils and certain localities is very evident in some districts. On the upper Paraguay places have been seen where the nests are quite thick over certain areas, while there were none, or but few, on an adjoining area. Wherever these marked contrasts have been observed, however, they have apparently been due to a difference in the amount of moisture in the ground. I have thought that the white ants are sometimes found in rather wet ground, because they are there comparatively free from the attacks of their enemies, the true ants.

Opinions of Brazilians in regard to the distribution of the termites' nests vary considerably; some think they are more abundant in the open campo regions than in the forests; others think they prefer fields; still others think they are favored by a dry climate. All of these views appear to have more or less support. I have much doubt, however, about the theory of their preferences for campos. It is true that they do appear very abundant in the campo regions, but I am of the opinion that the apparent abundance is deceptive and due to the fact that all the nests are visible at once over a wide area (see plate 35, figure 2), while in a forest-covered area no nests, or but few nests, can be seen on account of their being concealed by the dense vegetation. This impression has been deepened by the fact that in several instances where the forests have been cleared away the mounds of the white ants appear to be quite as abundant as they are in the old clearings or on the open campos.

Further support is given this theory by Maximilien, Prince de Wied-Neuwied, who, in speaking of the white ants' nests near Conquista, in the southwestern part of the State of Bahia, says that they are extremely abundant in covered and wooded places.[55]

RELATIONS TO VEGETATION

Compared with the true ants, the white ants are harmless. At least they do not attack crops and animals or render certain localities uninhabitable. The harm they do to agriculture is confined to the mere encumbrance of the ground by their big, hard, rock-like nests. They do, however, destroy wood used in the construction of fences, houses, bridges,

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[55] Voyage au Brésil, vol. iii, p. 129. Paris, 1822.

and furniture, and they sometimes burrow into books and papers that are left to stand for a long time undisturbed.

I quote below some remarks of other writers in regard to the destruction of timbers by termites, but I must add that I am disposed to question the rate at which these insects are said to destroy wood. My own observations lead me to conclude that the idea expressed by Drummond and others that a piece of furniture may be destroyed in a night is simply a picturesque way of putting it. In the first place, there are certain kinds of wood (in Brazil at least) that the termites do not attack at all. I am unable to say just now what kinds they are, but it is a matter of common information among Brazilian carpenters and cabinet-makers.

In the second place, the method of discovery of their destructive work frequently leaves an erroneous impression. In accordance with their general habit of keeping away from the light, termites attack a piece of wood that forms a part of a building from within. Their work does not appear at the surface at all, and it may be carried on for months, or even for years, without its being discovered. But some day a window-sill crushes in, a door-post is shattered by a trifling blow, or a rafter gives way without its ever having been suspected that they were being attacked by the cupim. The suddenness of the discovery not unnaturally leads to the unwarranted inference that all this work was done during the preceding night.

The following quotation is taken from pages 78-83 of Dr. Henry Drummond's little book called "Tropical Africa," was has an interesting chapter on white ants (pages 77-94):

"The termite lives almost exclusively upon wood, and the moment a tree is cut or a log sawn for any economical purpose this insect is upon its track. One may never see the insect, possibly, in the flesh, for it lives underground, but its ravages confront one at every turn. You build your house, perhaps, and for a few months fancy you have pitched upon the one solitary site in the country where there are no white ants. But one day suddenly the door-post totters and lintel and rafters come down together with a crash. You look at a section of the wrecked timbers, and discover that the whole inside is eaten clean away. The apparently solid logs of which the rest of the house is built are now mere cylinders of bark, and through the thickest of them you could push your little finger. Furniture, tables, chairs, chests of drawers, everything made of wood, is inevitably attacked, and in a single night a strong trunk is often riddled through and through and turned into matchwood. There is no limit, in fact, to the depredation by these insects, and they will eat books, or leather, or cloth, or anything, and in many parts of Africa, I believe, if a man lay down to sleep with a wooden leg it would be a heap of sawdust in the morning. So much feared is this insect now that no one in certain parts of India and Africa ever attempts to travel with such a thing as a

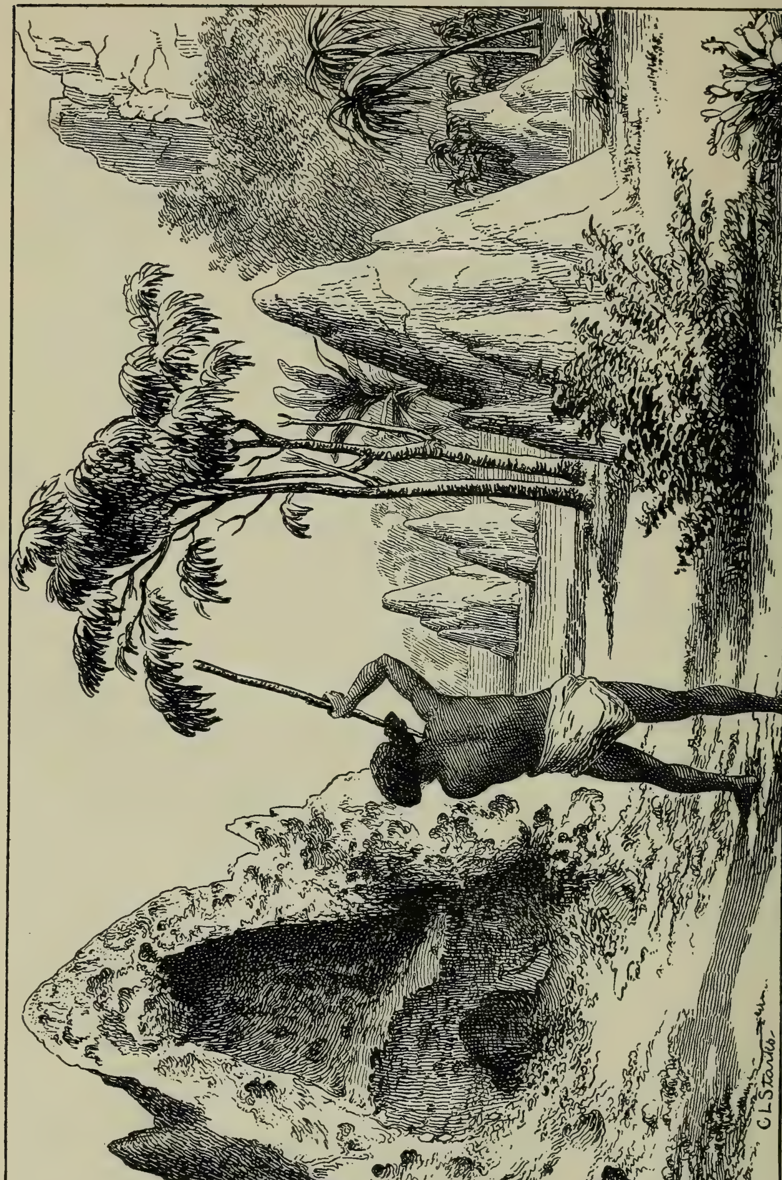

FIGURE 10.—*Nests of White Ants in Africa*

From "Tropical Africa," by Henry Drummond, opposite page 88 wooden trunk. On the Tanganyika plateau I have camped on ground which was as hard as adamant, and as innocent of white ants, apparently, as the pavement of St. Paul's, and awakened next morning to find a stout wooden box almost gnawed to pieces. Leather portmanteaus share the same fate, and the only substances which seem to defy the marauders are iron and tin."

The following extracts give an idea of how the work of the white ants looks from the point of view of the civil engineer:[56]

"The forests contain some varieties of hardwoods which would be suitable for permanent structures were it not for the ravages of insects. A species of white ant, called locally 'cupim,' appears to be the most destructive. These insects seem to attack timber bridges more than they do the timber ties, which are partially buried in the ground. They work in armies, building nests and artificial tunnels on the outside of bridge timbers and working into the heart of the timber from the ends. Although the largest of the 'cupims' yet observed is no longer than ¼ inch, so rapid and destructive is their action that the life of a timber bridge can hardly be considered more than two years. Frequently stringers and timbers whose ends butt together, appearing perfectly sound on the outside, are found in an incredibly short time to be so thoroughly honeycombed by this energetic little creature as to become unsafe members in a bridge or other important structure. No satisfactory method of preventing the action of the 'cupims' has yet been found here. Kerosene poured over a nest or into a tunnel will kill the insects within. The timber can then be scraped clean, but another army is soon at work again.

"Timber bridges have been built at various places to expedite the work and get the rail head to the front, but for permanency steel and masonry are the only materials suitable. A considerable quantity of pine lumber from the Southern States is being used for building purposes in Porto Velho. The experience up to date indicates that the insects do not attack this resinous wood, but not sufficient time has yet elapsed to prove conclusively that pine lumber will withstand their ravages. Ties of native lumber used in the track, either on account of the vibrations of passing trains or the partial covering of earth, resist the 'cupim' more successfully."

It should be noted that although the white ants are abundant in forests, I am not aware that they ever attack the living trees. They appear to eat only the dead trunks or dead limbs or bark. Many of them build their nests on the trees. Nests found high up on tree trunks are always, so far as I have observed, made of woody matter and not of earth. Those on trunks, only a meter or two above the ground, are often made partly of woody matter and partly of earth.

PHOSPHORESCENCE

It has been stated that some of the termites are luminous. On this subject see notes by Frederick Knab, *Science*, vol. xxx, October 22, 1909,

[56] John Y. Bayliss: The Madeira-Mamoré Railway. Engineering News, vol. lxii, p. 454. New York, October 28, 1909.

pages 574-575, and by J. C. Branner, *Science*, January 7, 1910, pages 24-25.

Herbert H. Smith, a thoroughly trustworthy entomologist, mentions phosphorescent termites near Santarem, on the lower Tapajos:

"There are white ant-hills along the sides (of the road)—pale glows of phosphorescent light, like coals in the ashes. . . . The phosphorescence is in the hills themselves, not, so far as I know, in the insects, and I believe that it is peculiar to the mounds of one or two forest species."[57]

FIGURE 11.—*White Ants' Nest in a Tree, Salitre Valley, State of Bahia*

J. C. Branner, 1907

Prof. Harold Heath, who has studied the termites of California, has given me the following statement:[58]

"Regarding the luminosity of termites, I can confidently assert that the three species (*Termopsis angusticollis*, *Calotermes castaneus*, and *Termes lucifugus*) living in the vicinity of San Francisco do not exhibit this peculiarity. The logs inhabited by these animals are occasionally infected by a species of phosphorescent slime mould (myxomycete), and when such colonies are disturbed at night, in the building of camp fires, for example, particles of brightly shining wood, or of the mould itself, may be seen attached to some of the individuals, but there is no true phosphorescence of the body. Furthermore, I have kept, during a period of several years, hundreds of colonies in glass jars placed in a cellar room, and these never showed any signs of the phenomenon in question."

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[57] Herbert H. Smith: Brazil, the Amazon, and the Coast, p. 139. New York, 1879.

[58] Stanford University, California, February 7, 1910.

Geologic Work

EARTH MOVED

The amount of earth brought to the surface by ants in a few instances has been given. The calculations at page 469 show that in one case the earth brought up would cover the ground to a depth of 22.25 contimeters. The estimate of Gounelle, mentioned at page 470, makes the earth brought up 15 centimeters thick. In neither of these cases is it known how long the building of the mounds occupied.

Mr. Darwin's study showed that the earthworms in many parts of England bring to the surface annually 10,516 kilograms of earth to the acre.[59] In order to compare the work of ants with that of earthworms, it would be necessary to know how long the ant-hills were in process of formation. Unfortunately I have no trustworthy means of determining the ages of the mounds. If we assume an average of 100 years for the age of the mounds over the area measured (an average which seems to me quite conservative in this case), the total work of worms and ants would compare as follows:

Total weight of earth brought to the surface in 100 years over 1 hectare (10,000 square meters):

By worms in England..................	2,598,500 kilograms
By ants in Brazil......................	3,226,250 kilograms

It is to be noted that the amount of work done in both instances is rather exceptional—that is, localities were selected favorable for exhibiting the activities of worms in one case and of ants in the other.

I have no trustworthy data showing the amount of earth brought to the surface by termites over a definite area. The places seen where the nests were most abundant were in low, inaccessible grounds on the upper Paraguay. My impression is that in those particular localities there was less earth brought up than in the case of the true ants cited above.

The sizes of individual white ants' nests were frequently measured. One of the largest I ever saw in Minas Geraes was 6 meters high and 8 meters in circumference 2 meters above the ground, and contained 30.55 cubic meters of earth, no account being taken of the porous nature of the structure, which would probably reduce this total by 3 or 4 cubic meters.

Another unusually large mound in the State of Minas was 4 meters high and 7 meters in circumference 2 meters above the base, and contained 15.59 cubic meters of earth. These are individual cases, however,

[59] Charles Darwin: The formation of vegetable mould through the action of worms, p. 305. New York, 1882.

and I am unable to say how large an area the contents can properly be distributed over, how long the termites were in doing the work, or how large the colonies were that made them.

In the case of the white ants, the earth undergoes some process of digestion and passes through the bodies of these insects, so that the chemical effect is probably more important than the mere upturning it gets from the true ants.

ORGANIC MATTER

The true ants carry into their burrows enormous quantities of leaves and other organic matter. These leaves must yield either directly or indirectly organic acids, which help attack the soil, the minerals, and the rocks with which they come in contact.

The organic matter carried into their burrows by the termites consists chiefly of the decayed wood and other vegetation eaten by them. These materials, however, can not fail to contribute organic acids that help attack the minerals of the soil and adjacent rocks.

OPENINGS IN THE SOIL

The extensive subterranean excavations, especially those of the true ants, permit the freer circulation of atmospheric air and of carbon dioxide. These channels must also serve from time to time for the passage of meteoric waters, and their great extent and ramification must hasten very considerably all the processes of atmospheric disintegration and alteration of soils, minerals, and rocks.

Unfortunately we have no observations at present that enable us to give quantitative values to these underground agencies and activities. We only know that the openings beneath the surface are rudely equal to the amount of soil in the above-ground structures.

Résumé

Ants and termites are vastly more numerous in tropical America than they are in the temperate regions.

They show a marked preference for, or rather their structures stand up better on, clayey than on sandy soil.

They affect the geology, especially the soil and subsoil, both directly and indirectly.

Directly:

1. By their habits of making underground excavations that radiate from a central nucleus and often aggregate several miles in length.

2. By opening the soil to atmospheric air and gases.

3. By bringing to the surface large quantities of soil and subsoil.

4. By introducing into their subterranean excavations large quantities of organic matter which must yield acids that affect the soil and the subjacent rocks.

5. By using these excavations for habitations and the production of gases that attack the soil and its contained minerals.

Indirectly:

6. By the periodic passage and circulation of meteoric waters through their extensive tunnels.

7. By affecting the availability of the soil for agricultural purposes.

8. By affecting the habitability of the land by man.

9. By the destruction of crops.

10. By the consumption (by termites) of dead plants and of timbers and lumber used in houses and for the manufacture of furniture, machinery, etcetera.

Although the data available are defective, we seem to be warranted in concluding that ants and termites are quite as important geologic agents in tropical America as are the earthworms of temperate zones.

They are also factors of great importance from an agricultural, economic, and social point of view.

POSTSCRIPT

Since this article was in type I have received the following letter from my Brazilian friend, Dr. Joaquim Lustosa, in regard to the subject of the luminosity of termites mentioned on pages 491-492. The letter is dated Lafayette, State of Minas Geraes, Brazil, July 8, 1910:

"I have just received authentic information to the effect that in the State of Matto Grosso, in the low, swampy lands along streams, and especially in the rainy months beginning with October, myriads of fireflies are seen covering the ground. My informant, who has lately come from the upper part of Matto

Grosso where it joins Bolivia, tells me that he has seen at night many of the nests of white ants that have been abandoned by the ants themselves entirely covered by fireflies that come from the small openings over the whole surface of the ant-hill. Is it possible that the fireflies select these abandoned ant-hills as places in which to grow their larvæ? . . . Unfortunately I have never observed anything of the kind hereabout, though I have been interested in the subject in order to furnish you information."

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 21, PP. 497-516 SEPTEMBER 10, 1910

INTERNAL CHARACTERS OF SOME MISSISSIPPIAN RHYNCHONELLIFORM SHELLS[1]

BY STUART WELLER

(Presented by title before the Society December 31, 1909)

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[1] Manuscript received by the Secretary of the Society April 29, 1910.

Introduction

Among all the Paleozoic brachiopods no type of shell configuration has greater range, greater distribution, or greater representation than the rhynchonelliform shells, and previous to the appearance of the great work on the Genera of Paleozoic Brachiopoda, by Hall and Clarke,[2] the more common custom was to refer all these shells to the genus *Rhynchonella.* It was pointed out by these authors, however, that the genotype of *Rhynchonella, R. loxia* Fischer, from the Upper Jurassic fauna of Russia, was, in its assemblage of external and internal characters, clearly distinct, generically, from any of our Paleozoic forms. They recognized, furthermore, no less than sixteen generic or subgeneric groups of rhynchonelliform shells in the Paleozoic faunas, to which either new names were given or for which previously published names were revived. No attempt was made by these authors to distribute all the species of Paleozoic Rhynchonelloids in their proper genera, but in his "Synopsis of American Fossil Brachiopoda" Schuchert[3] has attempted to so distribute the species so far as was possible. More than a hundred species, however, were allowed by Schuchert to remain in the genus *Rhynchonella,* because their internal characters had never been investigated and it was impossible to place them properly without such an investigation.

The present study is an attempt to determine the essential generic characters of some of the rhynchonelliform shells of the Mississippian faunas of the Mississippi Valley basin. The method of study has been to grind down the shells from the beak toward the front, on a carborumdum wheel, the surface being polished and careful cross-section drawings being made at frequent intervals. From the drawings of these serial sections the internal arrangement of the septa and other lamelliform plates, the hinge-plate, crura, spondylia, and cruralia can be interpreted with ease. The investigation has been extended to include certain rhynchonelliform shells which have been referred to the Pentamerid genus *Camarophoria* by Hall and Clarke and by Schuchert, all of which were originally described as members of the genus *Rhynchonella.*

Camarophoria King[4]

CAMAROPHORIA SCHLOTHEIMI (VON BUCH)

At the outset of the investigation it is important to determine the essential differences between *Rhynchonella,* used in its broad sense, and

[2] Paleontology of New York, vol. viii, parts 1 and 2 (1891-1894).
[3] Bulletin of the U. S. Geological Survey, No. 87 (1897).
[4] Superfamily Pentameracea Schuchert.

Camarophoria. Hall and Clarke have referred all those rhynchoneliform shells possessing a median septum in each valve, a ventral spondylium, and a dorsal cruralium to *Camarophoria,* and their diagnosis of that genus is clearly made, at least in part, from such rhynchonelliform shells as *R. subcuneata* and *R. subtrigona,* which are illustrated by them as typical of the genus. For the present study the essential characters of the genus *Camarophoria* have been determined by grinding specimens of *C. schlotheimi* from the Permian of Germany. Drawings of a series of eleven cross-sections of this shell are here persented in figure 1. The most diagnostic characters of the genus are found in the brachial valve where the hinge-plate is undivided and is supported by a strong median septum. From the lateral faces of the median septum a pair of horizontal processes arise close to the posterior extremity of the shell (figures 1*c, d, e*), which at first slope broadly and then curve more narrowly

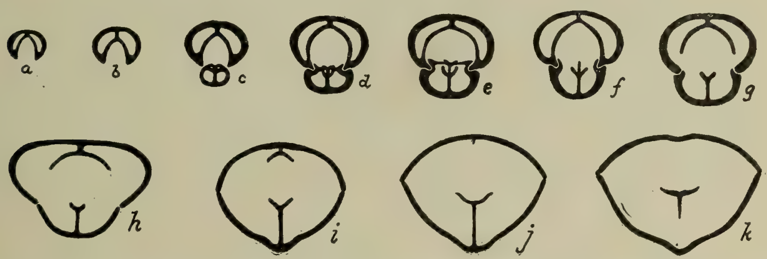

FIGURE 1.—*Cross-sections of the rostral Portion of Camarophoria schlotheimi (von Buch)*

This series of eleven cross-sections (× 2½) is from a specimen from the Permian of Pössneck, Germany

toward the hinge-plate with which the distal portions of the processes are joined posteriorly. Before the articulation of the valves is passed, however, the distal margins of the processes become free from the hinge-plate (figure 1*e*), and they constitute the two sides of a concave cruralium supported by a median septum from the floor of the valve, and in turn bearing a continuation of this septum along the middle line of its concave side which supports the undivided hinge-plate. The hinge-plate terminates abruptly in front, and is doubtless continued anteriorly in the crura, although these processes were not preserved in any of the examples sectioned. The cruralium continues anteriorly beyond the termination of the hinge-plate, and for a short distance the continuation of the median septum upon the concave side of the cruralium persists (figure 1*f*), although it becomes rapidly reduced and soon disappears. The cruralium continues with increasing elevation from the floor of the valve and increasing width to near the middle of the shell, and is even extended somewhat beyond the anterior limit of the median septum upon the floor of the valve.

In the pedicle valve the hinge-teeth are supported by strong dental lamellæ which are joined to form a broad spondylium supported by a median septum from the floor of the valve. Beyond the articulation of the valves the inner margins of the lamellæ become free. The spondylium is much broader and deeper than the cruralium of the opposite valve and is attached to the floor of the valve by a much lower median septum; it rapidly becomes shallower and narrower anteriorly, terminating before the cruralium of the brachial valve has reached its maximum expansion. The median septum continues a short distance beyond the extremity of the spondylium, but quickly disappears. Hall and Clarke[5] mention "two accessory supporting lamellæ abutting on one side against the outer surface of the converging dental plates, and on the other against the interior cardinal surface of the valve," but these have not been observed in any of the specimens sectioned, although they are present in at least two of the species referred to the genus *Camarophoria* by the same authors, *C. subcuneata* and *C. subtrigona*, neither of which species possess the true cruralium of the brachial valve which is so conspicuously developed in *C. schlotheimi*.

CAMAROPHORIA HAMBURGENSIS N. SP.

Among the Mississippian species which have been investigated, only two possess the essential characters of *Camarophoria* as exhibited by the genotype, and neither of these were referred to the genus by Hall and Clarke. The first is an undescribed species which may be designated as *C. hamburgensis*. It occurs commonly in the thin Hamburg oolite bed near the base of the Kinderhook at Hamburg, Calhoun County, Illinois.[6] The species occurs for the most part as detached valves, and a series of sections of both the pedicle and brachial valves is shown in figure 2. In the brachial valve this species is essentially like *C. schlotheimi* except that the lateral processes of the median septum, which are produced into the cruralium, arise nearer the floor of the valve, and their distal margins do not curve up sufficiently to become attached to the under surface of the hinge-plate, but always remain free (figures 2*k*, *l*). As in *C. schlotheimi* the median septum appears to pass through the cruralium in the apical portion of the valve as a support to the hinge-plate, and after it has ceased to render this support it is continued as a gradually disappearing

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[5] Paleontology of New York, vol. viii, part 2, p. 213.

[6] Transactions of the Academy of Science of Saint Louis, vol. xvi, p. 465.

median ridge along the concave side of the cruralium (figures 2*m, n, o*), the cruralium itself gradually increases in elevation and in width, finally becoming narrower and terminating abruptly. In the pedicle valve the

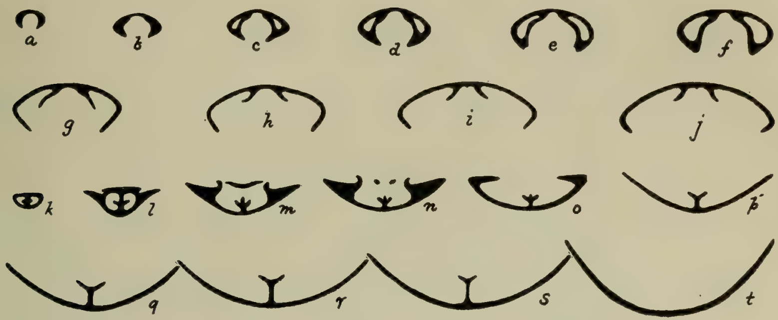

FIGURE 2.—*Cross-sections of the rostral Portion of the Pedicle Valve, and a Like Series of the Brachial Valve, of Camarophoria hamburgensis n. sp.*

This series of ten cross-sections (× 2½) is from specimens from the Kinderhook oolite at Hamburg, Calhoun County, Illinois

dental lamellæ are not joined to form a true spondylium, supported by a median septum from the floor of the valve, but they do form a spondylium-like process which rests directly upon the floor of the valve.

CAMAROPHORIA EXPLANATA (*McCHESNEY*)

A second species which is apparently a typical member of the genus *Camarophoria* is *C. explanata* (McChesney), which was referred to the genus *Pugnax* by Hall and Clarke. Externally this species closely resembles certain rhynchonelliform shells which have commonly been referred to *Pugnax*. The example illustrated by Hall and Clarke was a very perfect sulphur cast of McChesney's type specimen, which of course gave no indication of median septa in either valve and was naturally referred to *Pugnax*, but these characters were observed by Schuchert, who correctly referred it to *Camarophoria*.[7] In figure 3 a carefully prepared series of sections of this species is shown. The lateral processes from the sides of the median septum of the brachial valve are short and are situated high above the floor of the valve (figures 3*c, d, e*). In the section nearest the apex of the brachial valve these cruralium processes are apparently consolidated with the beginning of the hinge-plate (figure 3*b*), but the separation is complete from its origin, the distal margins of the processes not being joined to the under side of the hinge-plate for a short distance, as in *C. schlotheimi*. The median septum rising from the concave floor

[7] Bull. of the U. S. Geological Survey, No. 87, p. 162.

of the cruralium continues to the anterior margin of the hinge-plate, and even beyond, where it supports the bases of the crura (figure 3*f*), but beyond this point it is rapidly reduced and soon disappears. The cruralium is narrow, never attaining the width of that in the other two species which have been described, but becomes gradually wider toward the front; it becomes highly elevated above the floor of the valve anteriorly and is produced beyond the base of the median septum. The crura are strongly curved toward the opposite valve soon after the disappearance of the supporting median septum (figure 3*g*). In the pedicle valve the dental plates are curved toward the median line of the valve and form a spondylium which rests directly upon the floor of the valve posteriorly, but is supported by a low median septum anteriorly; it is not continued so far toward the front of the shell as is that of the brachial valve.

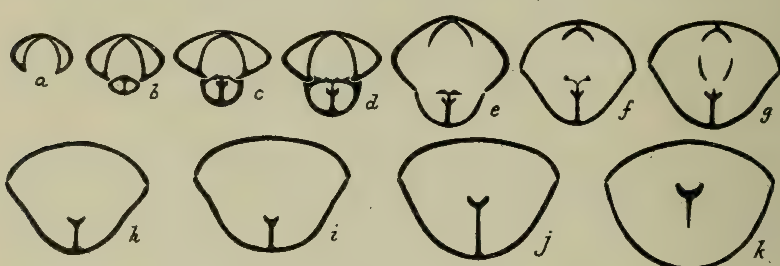

FIGURE 3.—*Cross-sections of the rostral Portion of Camarophoria explanata (McChes.)*
This series of eleven cross-sections (× 2½) is from a specimen from the Chester limestone of Illinois

The development of a true cruralium in the brachial valve is considered as the essential generic character of the three species just described. This cruralium is fundamentally different from the cruralium-like crural cavity between the lateral portions of the divided or undivided hinge-plate of many of the rhynchonelloid shells, which does not continue anteriorly beyond the hinge-plate and which does not support, along the median line of its concave surface, a continuation of the median septum. The criterion which has come to be used during late years for the placing of a rhynchonelliform shell in the genus *Camarophoria*—that is, the presence of a median septum in each valve—must give way to the character of the cruralium of the brachial valve. Many rhynchonelloid shells possess a distinct median septum in the brachial valve, and the fact that the dental lamellæ of the pedicle valve converge somewhat more rapidly in some examples and become joined as they reach the floor of the valve, or even before they reach it, and thus give rise to a median septum, is not sufficient basis for placing them in a different family, and even in a different order, as has been done by some students of the brachiopods. The presence or absence of the pedicle median septum in the true Rhynchonelloids is dependent solely upon the modification of certain elements, the dental lamellæ, which are present in all of the shells. The cruralium of the brachial valve, on the other hand, as developed in the species of *Camarophoria*, is a totally distinct morphologic element in the structure of the shell, and its presence is well worthy of recognition as of more than generic importance.

TETRACAMERA N. GEN.[8]

TETRACAMERA SUBCUNEATA (HALL)

Among the rhynchonelliform shells possessing a pedicle median septum, and referred for the first time to the genus *Camarophoria* by Hall and Clarke, is *Rhynchonella subcuneata* Hall. A series of cross-sections

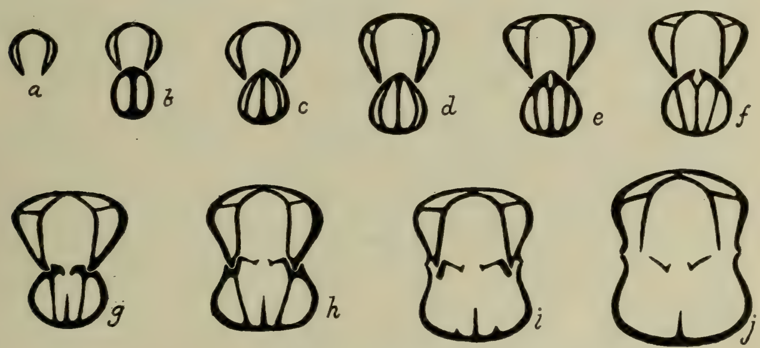

FIGURE 4.—*Cross-sections of the rostral Portion of Tetracamera subcuneata (Hall)*

This series of ten cross-sections (× 2½) is from a specimen from the Salem limestone of Indiana

of this common species of the Salem limestone is shown in figure 4. The median septum of the brachial valve is undivided at the apex of the valve (figures 4*b*, *c*, *d*), but before the articulation of the shell is reached a median incision is formed internally which is at first arched over (figure 4*e*), but soon becomes open on the cardinal side by the incision between the lateral divisions of the hinge-plate (figure 4*f*). This cruralium-like or crural cavity[9] is very short, not even extending anteriorly to the articulation of the valves, although the median septum continues with gradually decreasing height, sometimes to near the middle of the valve.

[8] Superfamily Rhynchonellacea Schuchert.

[9] This cavity is morphologically different from the cruralium of *Camarophoria*, and will hereafter be referred to as the *crural cavity*.

This structure is totally different from that of *Camarophoria*, in which a true cruralium is developed between the level of the hinge-plate and the floor of the valve, and continues as far anteriorly or even beyond the base of the median septum. The character of the median septum and crural cavity in this species is essentially identical with that of *Camarotœchia* and of several other undisputed rhynchonelloid genera. The species possesses, in addition to the median septum, two lateral lamellæ in the brachial valve which originate on the floor of the valve on either side of the base of the median septum and abut against the inner cardinal surface of the valve at their opposite extremity (figures 4*c, d, e, f, g, h*), these lamellæ, with the median septum, dividing the apical portion of the valve into four compartments. Anteriorly these lateral septa support the two lateral divisions of the hinge-plate directly opposite the hinge-sockets, to a point beyond where the inner margins of the divisions of the hinge-plate are supported by the divided median septum. These lateral lamellæ terminate abruptly, beyond the line of articulation of the hinge, and disappear entirely while the median septum is still considerably elevated.

In the pedicle valve the dental lamellæ are strongly developed and curve toward the median line as they approach the floor of the valve, forming a spondylium which rests directly upon the inner surface of the valve posteriorly, but which is raised upon a low median septum anteriorly. From the outer surface of each dental lamella a nearly horizontal plate passes across each lateral rostral cavity, joining with the inner surface of the outer shell wall. These lateral buttress plates have been observed in only one other rhynchonelloid shell, *R. subtrigona* M. & W., and they are the two accessory supporting lamellæ mentioned by Hall and Clarke in their diagnosis of *Camarophoria*, but which are wholly wanting, as has been shown, in the genotype of that genus, and are not known to be associated with the characteristic brachial cruralium of that genus. The peculiar association of characters in this species is believed to be sufficiently distinct from other rhynchonelloid shells to be worthy of recognition as a distinct and as yet undefined generic type, for which the name *Tetracamera* is herewith proposed. The genotype of this new genus is *T. subcuneata* (Hall), and the only other species which can as yet be included in it is *T. subtrigona* (M. & W.), which is next to be described.

TETRACAMERA SUBTRIGONA (*M. & W.*)

Tetracamera subtrigona is another rhynchonelliform shell which was placed in the genus *Camarophoria* by Hall and Clarke. This species is much larger than *T. subcuneata* and is proportionally much broader. Its geologic horizon is the Keokuk limestone. The internal characters of the shell are exhibited in the series of cross-sections shown in figure 5. The rostral cavity of the brachial valve is divided by a median septum which is at first solid (figure 5*e*), but is soon excavated on the median line near the cardinal side of the valve. This median excavation is completely arched over to the line of articulation of the valves (figures 5*f, g, h, i*), beyond which it is open on the cardinal side by a narrow, median, slit-like incision (figures 5*j, k, l*), thus forming a crural cavity which differs from that of *T. subcuneata* in having a much greater anterior extension and in having the median incision on the cardinal side much narrower;

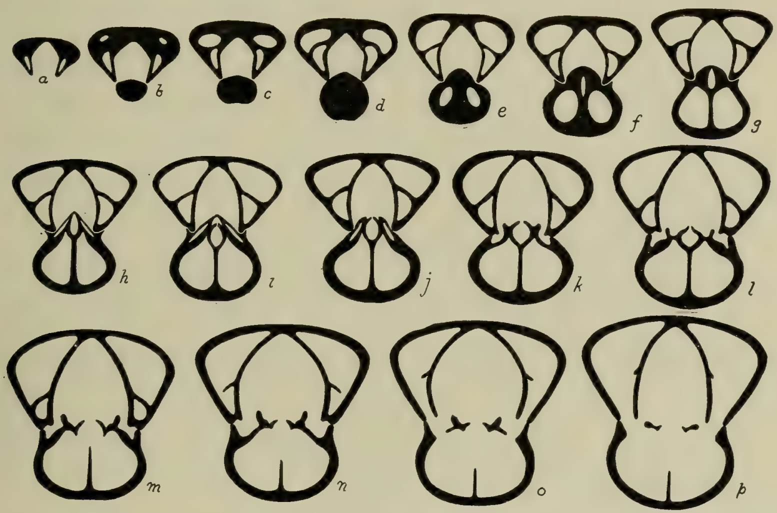

FIGURE 5.—*Cross-sections of the rostral Portion of Tetracamera subtrigona* (*M. & W.*)
This series of sixteen cross-sections ($\times$ 1¼) is from a specimen from the Keokuk limestone of Keokuk, Iowa

this structure, however, is totally different from that of the true cruralium of *Camarophoria*. At the line of articulation of the valves a shallow, broad, oblique cavity originates on each side of the central crural cavity (figures 5*h, i, j*), whose bounding wall on the cardinal side is much thinner than the inner wall. The inner walls may perhaps be compared with the two lateral septa of the rostral portion of the brachial valve of *T. subcuneata*, although their position is very different, their inner extremities abutting against the outer surface of the walls of the crural cavity and their outer extremity against the inner surface of the sides of the valve. Shortly after the origin of these lateral, oblique cavities, the crural cavity is differentiated into two portions (figure 5*i*) by the outgrowth from its inner surface of a pair of lateral processes which nearly meet in the median line; the two portions of the cavity thus formed are of unequal size; the one toward the cardinal side is smaller, subcrescentic in form, and is completely arched over, as was the undivided cavity posteriorly. The arched covering of the smaller crescentic cavity quickly disappears and the slitlike, median, cardinal incision of the crural cavity opens freely toward the interior of the shell (figures 5*j, k, l*). The lateral, oblique cavities on each side of the central crural are inclosed upon the cardinal side but for a short distance (figures 5*h, i, j*), but the inner walls continue as supporting plates abutting against the outer surface of the walls of the crural cavity internally and against the inner surface of the lateral walls of the valve externally (figures 5*k, l*), and they continue beyond the anterior extremity of the crural cavity, giving support to the crural bases (figures 5*m, n*). The median septum continues well toward the anterior extremity of the valve with gradually decreasing height.

In the pedicle valve of this species the dental lamellæ unite to form a spondylium which rests directly on the floor of the valve, and each plate is supported by a lateral buttress plate connecting the outer surfaces of the dental lamellæ with the inner surfaces of the lateral walls of the valve, these structures being essentially as in *T. subcuneata*, although the buttress plates are situated nearer the cardinal margins of the valves, and they slope toward the cardinal margin in passing from the inner to their outer extremities. Shortly before the inner margins of the dental lamellæ become free from the cardinal margins of the valves these buttress plates cease to reach to the inner surfaces of the lateral walls of the valve, and continue as gradually decreasing processes on the outer surfaces of the dental lamellæ (figures 5*n, o, p*).

In the internal structure of its pedicle valve this species is essentially like *T. subcuneata*, and it is therefore placed with it in the genus *Tetracamera*, but the structure of the brachial valve is unique among all the species examined, and it is possible that these characters should be considered as of sufficient importance to justify the establishment of a distinct genus for the species.

RHYNCHOTETRA N. GEN.

RHYNCHOTETRA CAPUT-TESTUDINIS (WHITE)

Another rhynchonelliform shell referred to the genus *Camarophoria* by Hall and Clarke, apparently because of the presence of a median septum in each valve, is *Rhynchonella caput-testudinis* White. This species has a peculiar external configuration, differing markedly from all other rhynchonelliform shells of the Mississippian faunas in its elongate, triangularly subovate form, its coarse plications, the great depth of the valves toward the beak, and the broad, concave lateral surfaces of the shell toward the beak. Material for the proper examination of the internal characters of a typical member of this species has not been available, but specimens of at least a closely allied form, which may perhaps be a distinct species, differing only in the arrangement of the coarse plications of the shell, have been investigated, and the series of cross-sections observed is shown in figure 6. In this shell the cross-section of the apical portion of the brachial valve is subtriangular in outline, and is divided by a median septum with a crural cavity internally, this cavity being arched over on its cardinal side (figure 6*a*). This condition persists to the be-

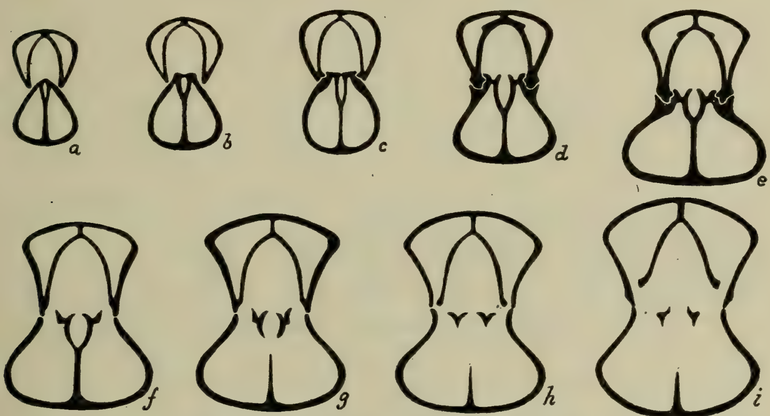

FIGURE 6.—*Cross-sections of the rostral Portion of Rhynchotetra caput-testudinis (White)?*

This series of nine cross-sections (× 2½) is from a specimen from the Burlington limestone of Missouri

ginning of the articulation of the valves, with the cardinal surface becoming broader and flatter (figures 6*b*, *c*), but beyond this point the cardinal surface is open and the divided portion of the median septum forms an open crural cavity (figures 6*d*, *e*). The outer surfaces of the processes forming this cavity are at first connected laterally with the two portions of the divided hinge-plate, but anteriorly this connection with the lateral margins of the valves ceases (figure 6*f*), and shortly thereafter the connection with the median septum is broken (figure 6*g*), the lateral walls of the crural cavity passing into the bases of the crura. The median septum continues well toward the front with gradually diminishing height. In this valve there is no structure comparable with the cruralium as seen in the typical representatives of *Camarophoria,* the crural cavity being identical in all essentials with the similar structure in many undisputed rhynchonelloid species.

In the pedicle valve the dental lamellæ are strongly developed and meet near the floor of the valve to form a spondylium which is supported by a median septum. Anteriorly the spondylium is progressively more elevated above the floor of the valve by the median septum. For a short distance, opposite the articulation of the valves, a pair of slight, lateral processes are present upon the outer surfaces of the dental lamellæ near their attachment to the median septum, which are possibly incipient lateral buttress plates such as are present in the genus *Tetracamera.*

Pugnax Hall and Clarke

PUGNAX PUGNUS (*MARTIN*)

The remaining species which will be considered here have never been removed from the family Rhynchonellidæ, although they have been distributed among several different genera, and in some cases their generic

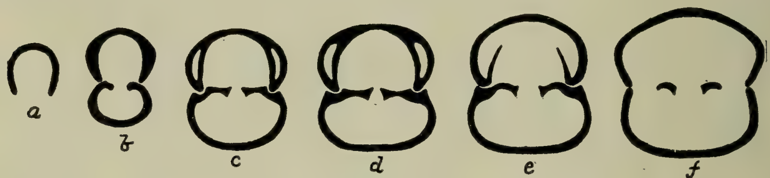

FIGURE 7.—*Cross-sections of the rostral Portion of Pugnax pugnus* (*Martin*)

This series of six cross-sections ($\times 2\frac{1}{2}$) is from a specimen from the Mountain limestone of Ireland

reference has clearly been incorrect. Hall and Clarke have referred no less than five Mississippian species to the genus *Pugnax*, and Schuchert has placed the same species in the genus, the generic characters most commonly depended upon being the external configuration of the shell, most especially the obsolescence of the plications except toward the anterior margin of the shell. In order to have a standard for the comparison of the American species referred to this genus, one of the typical species of the genus, *Pugnax pugnus*, from the Mountain limestone fauna of Ireland, has been investigated, and the cross-sections secured are shown in figure 7. The structure of this shell is exceedingly simple. No median septum is present in either valve; the hinge-plate of the brachial valve is divided to the apex, and the dental lamellæ of the pedicle valve are short. None of the Mississippian species referred to the genus *Pugnax* by Hall and Clarke or by Schuchert possesses this simple structure, and in fact no species possessing the combination of this arrangement of internal characters, with its peculiar external configuration, have been observed among those studied, and only two of the species which have been examined exhibit an entire absence of the median septum in the brachial valve.

Allorhynchus n. gen.

Allorhynchus heteropsis (Winchell)

One of the species in which an entire absence of the brachial median septum has been observed is *Rhynchonella heteropsis* Winchell, but in its external configuration it departs so widely from the typical form of *Pugnax* that no one has ever suggested that it be considered as a member of that genus. In figure 8 a series of cross-sections of this species is

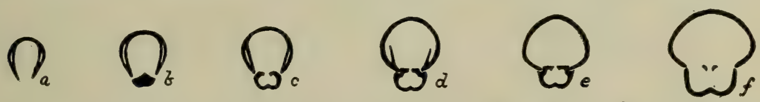

Figure 8.—*Cross-sections of the rostral Portion of Allorhynchus heteropsis* (*Winchell*)

This series of six cross-sections (× 2½) is from a specimen from the Kinderhook bed No. 4, at Burlington, Iowa

shown. The species can not be legitimately considered as a member of the genus *Pugnax* because of its external form, and on the other hand it can not be included in any of the recognized rhynchonelloid genera which it resembles externally, because of its internal features; it is therefore taken as the type of a new genus which may be called *Allorhynchus.* The species is marked by strong and angular plications which continue to the beaks of both valves, and in the umbonal portion of the brachial valve there is a distinct, median, longitudinal depression.

Allorhynchus macra (Hall)

Another species having the internal features of *A. heteropsis,* and lacking the external form of *Pugnax,* is *Rhynchonella macra* Hall, from the Salem limestone. A series of cross-sections of this species are shown in

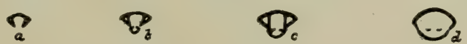

Figure 9.—*Cross-sections of the rostral Portion of Allorhynchus macra* (*Hall*)

This series of four cross-sections (× 2½) is from a specimen from Salem limestone near Alton, Illinois

figure 9. The species differs from *A. heteropsis* in its much smaller size, its much more compressed form, its much shallower and more obscure fold and sinus, and in the obsolescence of the plications toward the beak.

It agrees with that species in the absence of a brachial median septum, in the short dental lamellæ of the pedicle valve, and in the presence of a median, longitudinal depression in the umbonal portion of the brachial valve.

Camarotœchia Hall and Clarke

GENERAL CHARACTERISTICS

In the Devonian faunas of North America the genus *Camarotœchia* has an abundant representation. The members of the genus are characterized by the presence of a median septum in the brachial valve which is divided internally to form a short crural cavity between the two sides of the divided hinge-plate. The crural cavity is commonly very short, sometimes terminating posterior to the articulation of the valves, but the simple, unattached median septum sometimes continues with gradually diminishing height, well toward the center of the valve. In the pedicle valve members of this genus are supplied with well developed dental lamellæ which join the floor of the valve independently. In their external configuration members of the genus Camarotœchia are strongly and more or less angularly plicated, the plications continuing to the beak, and they possess a well defined fold and sinus.

CAMAROTŒCHIA CHOUTEAUENSIS N. SP.

In the Mississippian faunas a single well defined but undescribed species of Camarotœchia has been observed. It is a common form in the

Figure 10.—*Cross-sections of the rostral Portion of Camarotœchia chouteauensis n. sp.* This series of eight cross-sections (× 2½) is from a specimen from the Chouteau limestone of central Missouri

Chouteau limestone and may be called *C. chouteauensis*. A series of cross-sections of the species is shown in figure 10.

Wilsonia Kayser

WILSONIA GROSVENORI (HALL)

A species which was referred to the genus *Pugnax* by Hall and Clarke and by Schuchert is *Rhynchonella grosvenori* Hall. Internally this species possesses all the essential characters of *Camarotœchia,* as is shown in the series of cross-sections given in figure 11. Externally it is more or less subcubical in form, with comparatively fine plications and slightly depressed median sinus in the pedicle valve, which is greatly produced anteriorly at nearly a right angle to the plane of the valve. These char-

FIGURE 11.—*Cross-sections of the rostral Portion of Wilsonia grosvenori* (*Hall*)

This series of five cross-sections (× 2½) is from a specimen from the Salem limestone of Illinois

acters give the species much the aspect of members of the genus *Wilsonia*, to which genus it is here provisionally referred. The internal characters of typical members of the genus *Wilsonia* differ in no essential respect from Camarotœchia, and if the genus is worthy of recognition it must be distinguished by its external form.

Leiorhynchus Hall

LEIORHYNCHUS GREENEANUM (*ULRICH*)

Another rhynchonelloid genus recognized by Hall and Clarke, which has the essential internal characters of *Camarotœchia*, is *Leiorhynchus*. This genus is established primarily upon its external form, it being but

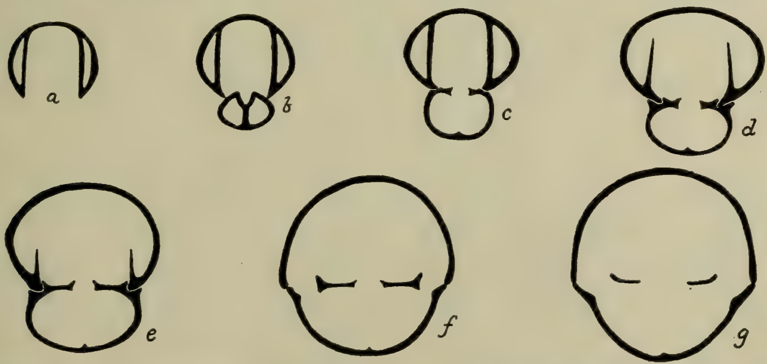

FIGURE 12.—*Cross-sections of the rostral Portion of Leiorhynchus greeneanum* (*Ulrich*)

This series of seven cross-sections (× 2½) is from a specimen from the Knobstone formation of southern Indiana

obscurely plicated, with its plications commonly better developed on the fold and sinus than upon the sides of the shell. A good example of this genus is *L. greeneanum* (Ulrich), from the basal Mississippian of southern Indiana, a series of cross-sections of which is shown in figure 12.

Pugnoides n. gen.

PUGNOIDES OTTUMWA (*WHITE*)

One of the rhynchonelloid shells which has been commonly referred by recent authors to the genus *Pugnax* is *Rhynchonella ottumwa* White. A series of cross-sections of this species is reproduced in figure 13, in which it is shown to possess all the essential internal characters of *Camarotœchia*. If, however, it is legitimate to recognize such genera as *Wilsonia* and *Leiorhynchus*, genera possessing essentially the same internal structure as

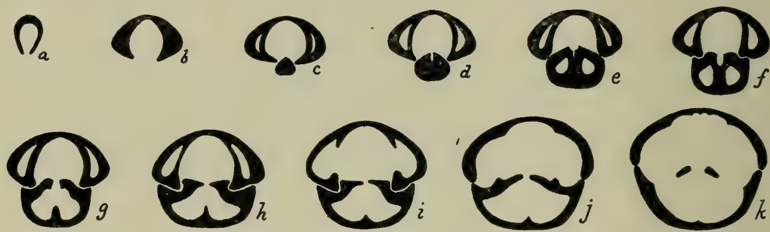

FIGURE 13.—*Cross-sections of the rostral Portion of Pugnoides ottumwa* (*White*)

This series of eleven cross-sections (× 2½) is from a specimen from the Pella beds of Iowa

Camarotœchia, and based primarily upon the external form and ornamentation of the shell, then *R. ottumwa*, with its external aspect of *Pugnax*, must also be excluded from *Camarotœchia*, and as there is no genus in which it can be placed, it becomes necessary to establish a new one for its reception. This genus may be called *Pugnoides*, with *P. ottumwa* as genotype.

Shumardella n. gen.

SHUMARDELLA MISSOURIENSIS (*SHUMARD*)

A species of rhynchonelliform shell from the Chouteau limestone was described by Shumard in 1855 as *Rhynchonella missouriensis*. The contour and ornamentation of the shell is peculiar, and it has commonly been referred to the genus *Pugnax* by recent authors, evidently because of its coarse plications, which become more or less obsolescent toward the beak. The presence of a strong median septum in the brachial valve, however, must exclude the species from that genus, and the internal characters of the shell are so different from other species that, associated as they are with the peculiar external forn , the species may be taken as the type of a new genus, *Shumardella*. A series of cross-sections of the shell is shown in figure 14. In this genus the median septum of the brachial valve is divided internally by a narrow median incision, which, however, is not open cardinally to f^rm an open crural cavity as in *Camarotœchia*, but is arched over, as . nown in figure 14*d*. The median septum is soon disconnected from the cardinal side of the valve (figure 14*e*), and continues with gradually decreasing height well toward the middle of the valve. With the disconnection of the median septum cardinally, the two plates forming the sides of the inclosed crural cavity continue as free plates extending into the cavity of the valve (figure 14*e*),

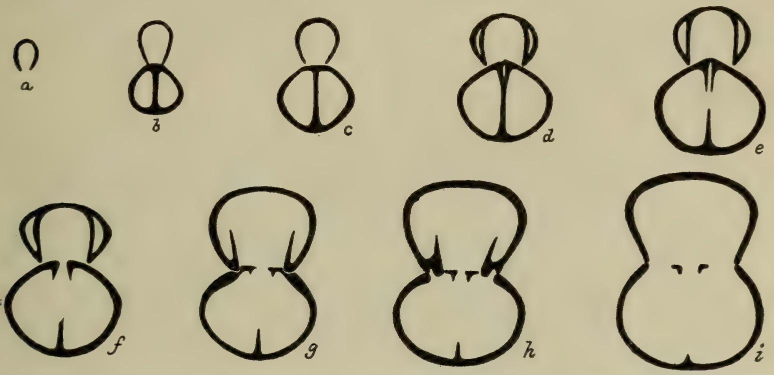

FIGURE 14.—*Cross-sections of the rostral Portion of Shumardella missouriensis (Shum.)*
This series of nine cross-sections (× 2½) is from a specimen from the Chouteau limestone of Missouri

the space between the plates is arched over cardinally for a time, but with the reduction of the width of these vertical plates the hinge-plate becomes divided just posterior to the articulation of the valves (figure 14*f*). Beyond the articulation of the valves the inner margins of the divided hinge-plate are produced anteriorly into the bases of the crura.

SHUMARDELLA OBSOLESCENS (HALL)

Associated with *S. missouriensis* in the Chouteau limestone is a smaller, more subglobular shell, with nearly obsolete plications, which has com-

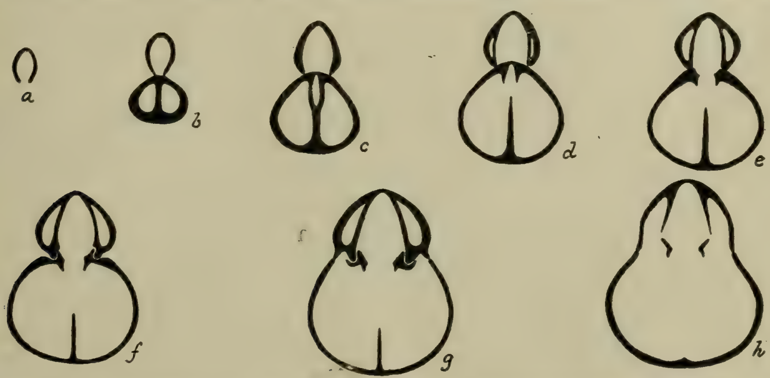

FIGURE 15.—*Cross-sections of the rostral Portion of Shumardella obsolescens (Hall)*
This series of eight cross-sections (× 2½) is from a specimen from the Chouteau limestone of Missouri

monly been considered as a variety of *S. missouriensis.* This shell is perhaps identical with *Rhynchonella obsolescens* Hall, from the Rockford limestone of Indiana; at least the external form is essentially the same, and it may be designated as *S. obsolescens* until the internal characters of the Rockford shells are investigated. A series of cross-sections of this shell is shown in figure 15, which shows that in its essential features it agrees with *S. missouriensis* and may be included in the same genus.

Rhynchopora King

GENERAL CHARACTERISTICS

The genus *Rhynchopora* has been established to include several rhynchonelloid shells which are known to possess a punctate shell structure, this shell structure being the essential character upon which the genus has been based. The internal structure of the shell has never been described, but on investigation several species seem to exhibit additional characters of generic importance. No opportunity has been afforded to examine the genotype of the genus.

RHYNCHOPORA PUSTULOSA (*WHITE*)

This species occurs in one of the Kinderhook formations at Burlington, Iowa, and a series of cross-sections of a typical representative of the species is shown in figure 16. After the second section the pedicle valve is

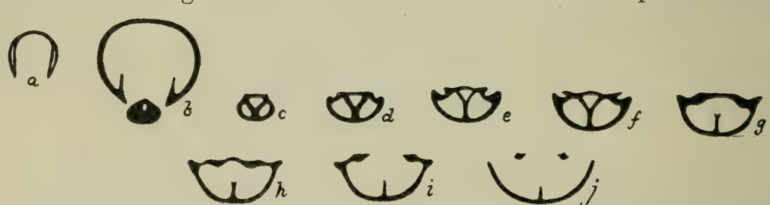

Figure 16.—*Cross-sections of the rostral Portion of Rhynchopora pustulosa* (*White*)
This series of ten cross-sections (× 2½) is from a specimen from the Kinderhook bed No. 4, at Burlington, Iowa

not shown in these figures, as it possesses no features of diagnostic value. In the brachial valve a well defined median septum is present which is divided to form a crural cavity as it approaches the cardinal side of the valve (figures 16*c, d, e, f*), but, unlike Camarotœchia, this crural cavity is roofed over by the undivided hinge-plate. Even after the median septum has become disconnected cardinally the undivided hinge-plate persists nearly to the point where the crusal bases become free (figures 16*g, h, i*). This character of the undivided hinge-plate is entirely different from any other generic group of Mississippian rhynchonelloids which has been investigated in these studies, and seems to be an additional character of generic value in *Rhynchopora.*

RHYNCHOPORA HAMBURGENSIS N. SP.

In the thin oolite limestone of the Kinderhook at Hamburg, Illinois,[10] a small rhynchonelloid shell occurs in great profusion. The shell structure is distinctly punctate and a series of cross-sections, reproduced in

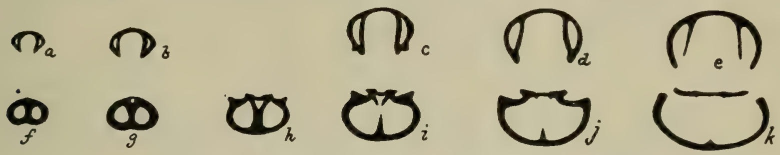

FIGURE 17.—*Five Cross-sections of the rostral Portion of the Pedicle Valve and Six of the Brachial Valve of Rhynchopora hamburgensis n. sp.*

These two series of cross-sections (× 2½) are from specimens from the Kinderhook oolite of Hamburg, Illinois

figure 17, shows that it has the same type of undivided hinge-plate as is present in *R. pustulosa.*

RHYNCHOPORA BEECHERI GREGER

Cross-sections of this shell have not been made, but a series of very excellent internal casts in chert exhibit not only its strongly punctate shell structure, but also the presence of an undivided hinge-plate similar to that in other members of the genus.

RHYNCHOPORA PERSINUATA (*WINCHELL*)

This species has not previously been referred to the genus *Rhynchopora,* but study of an excellent example of an internal cast of the species from the typical locality shows that the hinge-plate is undivided as in members of the genus, but the specimen is not preserved in such a manner as to exhibit either the presence or absence of the characteristic punctate shell structure. On examining all available examples of the species, however, one was observed in which the shell structure is distinctly punctate, so that the two essential characteristics of the genus *Rhynchopora* are known to be present.

RHYNCHOPORA ? COOPERENSIS (*SHUMARD*)

This species occurs somewhat commonly in the Chouteau limestone, but a diligent examination of all the examples which have been available for study has failed to demonstrate that the punctate structure of the

[10] Transactions of the Academy of Science of Saint Louis, vol. xvi, p. 465.

shell is present; but in its external features the shell is so like *R. persinuata* that the two species can scarcely be distinguished. A series of cross-sections showing the internal features of the species is reproduced in figure 18, and these show the characteristic undivided hinge-plate of

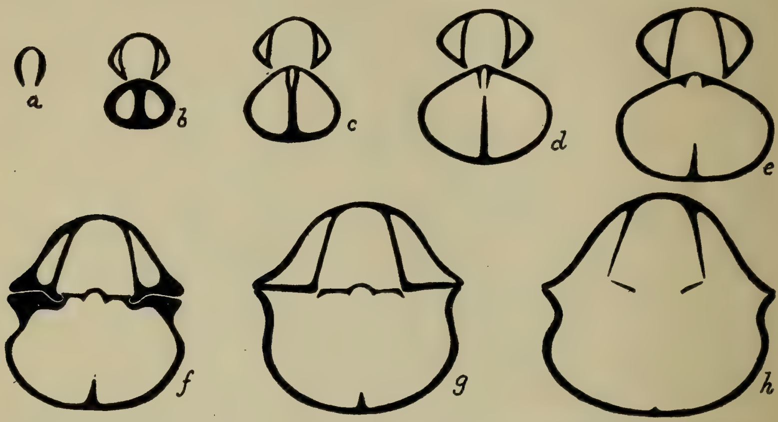

FIGURE 18.—*Cross-sections of the rostral Portion of Rhynchopora ? cooperensis (Shumard)*

This series of eight cross-sections is from a specimen from the Chouteau limestone of Missouri

Rhynchopora. Under these circumstances it seems to be safe to refer the species to that genus, although until the punctate shell structure has been observed the reference may be made with a query.

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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NEW LIGHT ON THE GEOLOGY OF THE WASATCH MOUNTAINS, UTAH[1]

BY ELIOT BLACKWELDER

(Presented extemporaneously before the Society December 28, 1909)

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INTRODUCTION

During the past season the writer, in company with Mr. J. M. Jessup and Mr. M. A. Becher, from the University of Wisconsin, made a somewhat detailed survey of parts of the mountains near Ogden, Utah, and were afforded glimpses of wider range both north and south. This paper will present in a disconnected way some of the more important results of the work. It can not lay claim to being a unified account of the geology of the range, for the opportunities of the party were not such as to permit a sufficiently comprehensive survey. The writer and his companions

[1] Published by permission of the Director of the U. S. Geological Survey.
Manuscript received by the Secretary of the Society April 19, 1910.

fully realize that they have only scratched the surface in a highly fertile field of geologic study.

The Wasatch Mountains, as defined by the U. S. Geographic Board, comprises two distinct parallel ranges which are separated by depressions 4 to 10 miles wide. The eastern range is often called the Bear River range or plateau. For the western portion, which flanks the Salt Lake plain, there seems to be no specific name. As it is the more conspicuous of the two ranges, it is here called the "Wasatch range proper." The field of study on which this paper is based includes that part of the western range which lies north of Weber River (near Ogden) as well as adjacent parts of the Bear River plateau.

Stratigraphy

Earlier Investigations

The general features of the geology of the Wasatch region have long been known from the reports of the King[2] and Hayden[3] surveys. No comprehensive general studies have been made since that time, but several geologists have investigated special problems, and thereby contributed important results. Walcott[4] has studied the Cambrian formations in both the main Wasatch and the Bear River ranges, and has divided them into many formations on the basis of abundant fossils. Weeks,[5] in addition to his work in company with Walcott, has inspected the Paleozoic rocks at various points in both ranges, and has made the only previous reconnaissance of the Carboniferous phosphate deposits. Unfortunately most of his results are still unpublished. The work of Boutwell,[6] in the Park City district, southeast of Salt Lake City, is important for the light it sheds on the stratigraphy of the Carboniferous and early Mesozoic formations. To him is due also a sounder interpretation of the complex structure of the central part of the Wasatch range. The existence in the Bear River range of Silurian and Devonian limestones identifiable by

[2] U. S. Geological Exploration of the 40th Parallel, vols. i, 1877, ii, 1877, iii, 1878; and S. F. Emmons: Amer. Jour. Sci., 4th ser., vol. xvi, 1903, pp. 139-147.

[3] U. S. Geographical and Geological Survey of the Territories: Idaho and Wyoming. Fifth Ann. Rep., 1872, Sixth Ann. Rep., 1873, and 11th Ann. Rep., 1877.

[4] C. D. Walcott: Cambrian faunas of North America. U. S. Geological Survey, Bulletin 30, 1886, pp. 38-39.

Cambrian sections of the Cordilleran area. Smithsonian Miscellaneous Collections, vol. liii, 1908, pp. 167-230.

[5] F. B. Weeks: Contributions to economic geology, 1906. U. S. Geological Survey, Bulletin 315, pp. 449-462. Also unpublished data.

[6] J. M. Boutwell: Stratigraphy and structure of the Park City mining district, Utah. Journal of Geology, vol. xv, 1907, pp. 434-458.

Provisional Correlation Table

Hague and Emmons, 1877.	Boutwell, Kindle, Walcott, and others, 1880–1909.	Period.
Permo-Carboniferous shales and limestone	Ankareh shale Thaynes formation Woodside shale	Lower Triassic or Permian
Upper Coal Measure limestone	Park City formation	Pennsylvanian
Weber quartzite	Weber quartzite Morgan formation	
Wasatch limestone	Mississippian limestone	Mississippian
Ogden quartzite[7]	Jefferson limestone	Devonian
	Paradise limestone	Silurian
	(Ogden quartzite) Shale and sandstone at Geneva[8] Box Elder limestone	Ordovician
Ute limestone	Saint Charles formation Nounan formation Bloomington formation Blacksmith formation Ute formation	Cambrian
Primordial slates	Pioche shale[9] { Spence shale Langston limestone	
Cambrian quartzites and slates	Brigham quartzite	
	Algonkian quartzites and slates	Algonkian
Archean	Archean gneiss and schist	Archean

fossils has been shown by Kindle.[10] Girty and Stanton have studied the fossils of the Carboniferous and later beds, but the results are not yet available in print. On the physiographic side, the more important contributions have been made by Gilbert[11] and Davis[12] on the subject of

[7] Not correlated with Jefferson limestone, but supposed at first to be Devonian; later assigned to Ordovician.

[8] Existence of Ogden quartzite disproved. Geneva formation occupies about the same horizon the Ogden was supposed to have.

[9] Langston and Spence members in Bear Lake district probably equivalent to the Pioche shale of Ogden region and southwestward.

[10] E. M. Kindle: American Journal of Science, vol. xxv, 1908, pp. 127-128, and Bulletin of American Paleontology, Ithaca, vol. iv, 1908, pp. 14-18.

[11] G. K. Gilbert: Lake Bonneville. U. S. Geological Survey, Monograph I, 1890.

[12] W. M. Davis: The Wasatch, Canyon, and House ranges, Utah. Bulletin of the Museum of Comparative Zoology, Harvard Collection, vol. xlix, 1905, pp. 17-56, and Mountains of the Great Basin, same, vol. xlii, 1903, pp. 128-177.

recent normal faulting and topographic development, and by Atwood[13] on the glacial features. Mention is not made in this list of numerous smaller contributions, all of which have had their value.

In the following pages the writer presents some additional information about Wasatch geology. It is to be hoped that so interesting and important a region will not long await the thorough study which it deserves.

SEPARATION OF CAMBRIAN FROM ALGONKIAN

The earlier explorations of the Wasatch range revealed beneath the oldest fossiliferous rocks a great series of quartzites and slates, having an estimated thickness of 12,000 feet. Walcott found the Olenellus fauna at the top of this succession, near Salt Lake City, and recommended that the great quartzite series should be placed in the Algonkian system, since it lay beneath the Olenellus horizon. The series is best exposed in Big Cottonwood Canyon, south of Salt Lake City, but it appears also in a line of low mountains which extend from the upper canyon of Ogden River northwest to the town of Brigham.

Up to 1909 no line of division had been found between the fossiliferous part of the Cambrian and the great mass of the quartzite-slate series. The geologists of the Survey of the 40th Parallel considered the entire succession conformable, and therefore called it all Cambrian. Walcott also regarded it as conformable, but applied the name Algonkian to the barren downward extension of the lower Cambrian. Two facts, however, suggest the existence of an unconformity within the quartzitic series: (1) The quartzite shows remarkable variations in thickness. Although 12,000 feet thick in Big Cottonwood Canyon, it is less than 1,500 feet thick at Ogden, is at least 10,000 feet thick northeast of Huntsville, is again 1,000 to 1,500 feet thick at Willard, and is several thousand feet thick at Brigham. These great fluctuations within short distances seem to demand a special explanation. (2) The conglomerate bands, of which there are many in the upper part of the quartzite series, contain more pebbles of quartzite than of all other rocks combined, and many of these quartzite pebbles bear a strong lithological resemblance to the bright-colored quartzites farther down in the supposed Algonkian.

The writer was not so fortunate, however, as to find the unconformity exposed until, at the close of the season, he visited Big Cottonwood Canyon. There, at a horizon roughly estimated about 1,500 feet beneath the top of the quartzite, a well marked conglomerate is exposed. It is

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[13] W. W. Atwood: Glaciation in the Uinta and Wasatch Mountains. U. S. Geological Survey, Professional Paper 61, 1909.

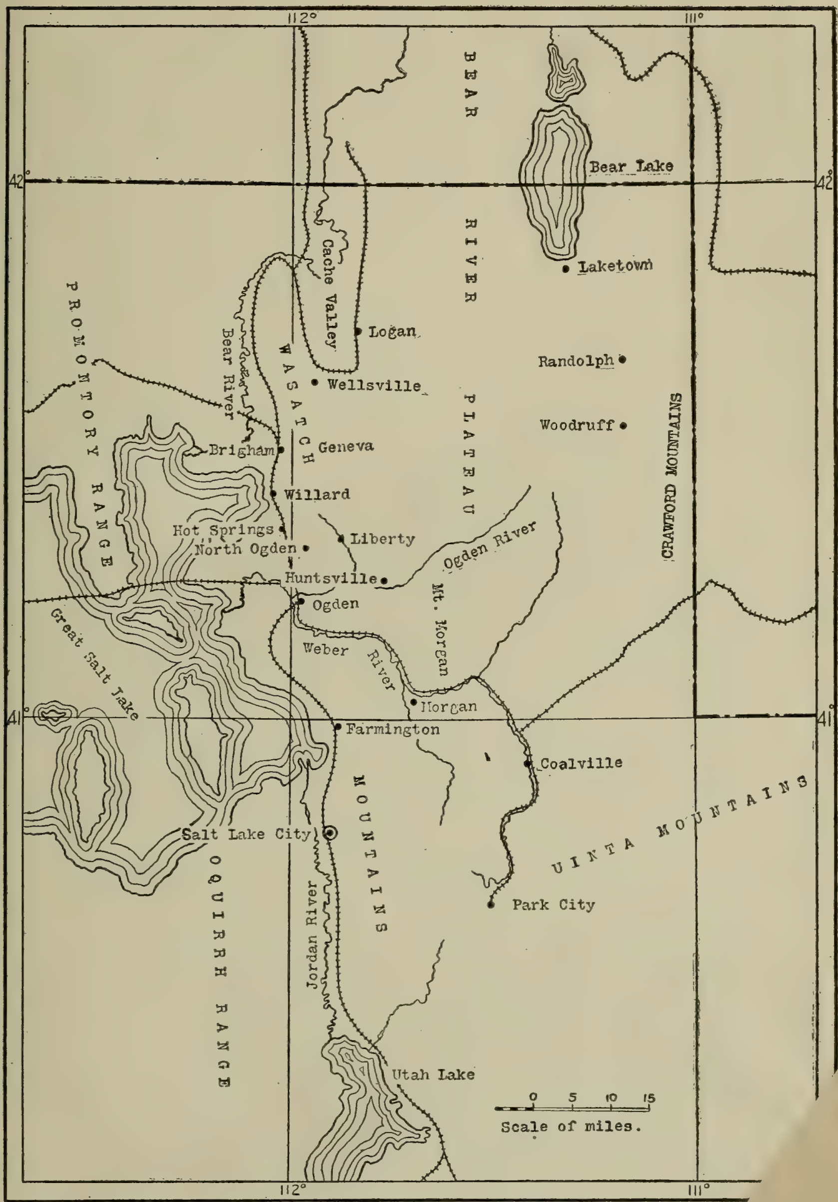

FIGURE 1.—*General Map of northeastern Utah*

several yards thick and is composed of rounded pebbles, largely of quartzite, with occasional pieces of gneiss and vein quartz. The contact was found first in the bottom of the canyon, was traced 500 feet up the south slope, and was found again on the front of the range two or three miles north of the mouth of the canyon. Between the two sets of beds there is but little angular discordance, but as seen from the south slope of Big Cottonwood Canyon the contact gradually truncates the individual

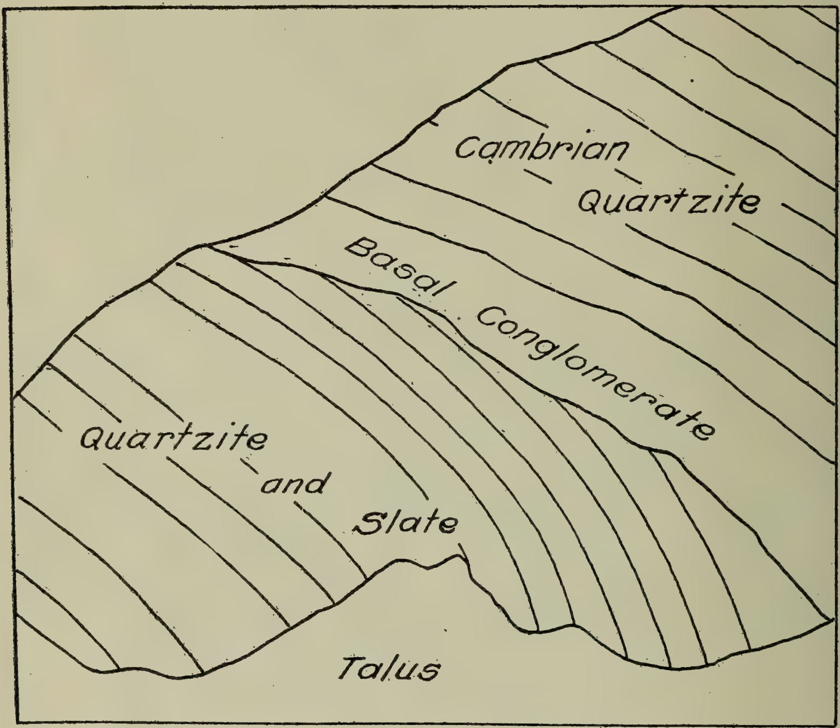

FIGURE 2.—*Diagram showing the Relations of the Cambrian and Algonkian Quartzites*
The locality is about 1½ miles below the Maxfield Mine in Big Cottonwood Canyon. The diagram is made from a poor photograph

layers of the underlying quartzite (see figure 2). The truncation of the beds may be inferred also from the relations of the conglomerate to the underlying rocks at different points. Thus, in the bottom of the canyon it lies on white quartzite; several hundred feet up the south slope it lies upon hard gray shale, and still higher on quartzite again. In the locality on the front of the range the conglomerate rests upon purple and gray shales at the point examined, but evidently passes over upon quartzite higher on the spur.

FIGURE 1.—CONGLOMERATE OF QUARTZITE PEBBLES AT THE BASE OF THE CAMBRIAN QUARTZITE IN BIG COTTONWOOD CANYON

FIGURE 2.—CAMBRIAN QUARTZITE RESTING ON ARCHEAN GNEISS AND OVERLAIN BY CAMBRIAN SHALE AND LIMESTONE AT WILLARD. THE SEQUENCE HERE IS UNBROKEN

EXPOSURES OF QUARTZITE PEBBLES AND CAMBRIAN QUARTZITE

It seems clear, therefore, that there is an unconformity not far below the top of the great quartzite-slate series, and it will probably be found to have a much wider distribution than now known. It corresponds in a general way with the unconformities which separate the Middle Cambrian from the Belt series of Montana and from the Grand Canyon series of Arizona.

Just below the fossiliferous Cambrian shales and limestones there is a quartzite 1,000 to 1,500 feet thick. This quartzite rests now on the eroded surface of the Algonkian quartzite and slate, and now on the much older gneiss and schist which are generally referred to the Archean. Walcott has named it the *Brigham* quartzite, but it may be seen most clearly at places such as Ogden and Willard, rather than at Brigham. The oldest fossils found in the shales are referred by Walcott to the Lower Cambrian. The Brigham quartzite may therefore be assigned also to the early Cambrian[14] and the quartzites and slates beneath the unconformity to the Algonkian. There is, however, an alternative view, advocated by Daly and others, that the oldest Cambrian faunas in the Rocky Mountains are Middle Cambrian and that the thin Brigham quartzite is the same in age; that the unconformity represents a brief time interval and that the great quartzite slate series is not Algonkian, but simply early Cambrian. Critical studies over a wide area are a necessary preliminary to the settlement of this question. It is to be remembered that the unconformity seems to imply the complete removal of the great quartzite series during the erosion interval and over wide areas. The time involved should therefore be more than a brief interruption.

INTERPRETATION OF THE ALGONKIAN QUARTZITE-SLATE SERIES

For the present the thick series of quartzites and slates lying below the unconformity just described will be assumed to be Algonkian, according to the prevalent view. In the two best known sections—that is, in Big Cottonwood Canyon and along the upper course of Ogden River—this system has many characteristics which harmonize with a particular interpretation of its origin. The base of the series has apparently not been seen anywhere.[15]

The prevailing rocks are quartzites or quartzitic sandstones variously colored. Here and there in the sandstone are many thin beds of con-

---

[14] Walcott considers the upper part of the quartzite Middle Cambrian, north of the Salt Lake district.

[15] Along the back slope of the main range from Ogden Canyon north almost to Brigham, there is a mass of folded dark slates and schistose graywackes which underlies the quartzite-slate series. The details of the succession and the relations of these beds are yet unknown, but will repay careful study at some later time. It is not improbable that two unconformable systems may be discovered.

glomerate in which the pebbles consist of quartz and quartzite well rounded and moderately well assorted. Many of the sandy beds are prominently cross-bedded, the cross-bedding having a relatively small amplitude. On the bedding planes ripple-marks, generally of the long parallel type, are of common occurrence.

At several horizons in the section, but especially in the lower portion, hard shales and slates are interbedded with the quartzites. The prevailing colors of these argillaceous members are dark purplish brown or bright green, but there are some which are distinctly black and others rich maroon. The purplish, maroon, and green beds are composed of poorly assorted material, consisting of clay and sand, with abundant mica flakes. Tension cracks have been found in them at several points and appear to be relatively common. About 2 miles northwest of the village of Liberty, in Weber County, there is a small mass of coal-black slate with imbedded pyrite crystals. The relations of this member are not observable, but it is evidently a part of the Algonkian sequence.

Excepting a few thin beds of brown dolomite interleaved with the slates northeast of Willard, no beds of limestone have been observed anywhere in the section. Likewise no fossils have been found, although considerable time was spent in search for them in beds of shale which have suffered little deformation and still less metamorphism and which preserve unmarred their original stratification. Walcott mentions the fact that the most promising shale beds in the Big Cottonwood Canyon section yielded no fossils to a painstaking search.

The significant characteristics of the Algonkian system in this region may then be summarized as follows: It consists of alternating beds of quartzite, slate, and conglomerate, which are variable from place to place; cross-bedding, ripple-marks, and mud cracks are prevalent. The materials are not well assorted, and in the sandy beds the prevailing colors are yellow, gray, and red, while purple, maroon, and green predominate in the shaly layers. There is apparently a general lack of limestone and of fossils.

Sedimentary deposits having a thickness of many thousands of feet have generally been assumed to be of marine origin. It is now well recognized, however, that thickness has no such necessary implication. Fluviatile deposits, such as the Siwalik formation of India and the California Valley sediments, are known to have great depth. In the Algonkian of the Wasatch region the absence of limestone from so great a thickness of rocks and the dearth of fossils in beds so little altered is in itself significant. The cross-bedding which is a characteristic feature of the strata at many horizons is indicative of shifting currents. The regularity of dip and the small amplitude of the cross-bedded structures implies currents moving in a single general direction, and currents of water rather than of wind. The uniformity of the cross-bedding in stratum after stratum may be taken to mean a constancy of conditions scarcely to be expected on a sinking sea bottom. The beds of conglomerate locally interstratified with sandstone show that the currents were alternately stronger and weaker at the same point. The ripple-marks are of less significance than some other features, although they indicate shallow water and are in harmony with the testimony of the other features. Barrell[16] has called attention to the fact that tension cracks are best developed on muddy flats bordering streams or lakes subject to considerable seasonal changes of climate. While it is possible to have them formed along tidal flats, such situations are probably much less favorable to their preservation. The imperfect assortment of the materials appears to indicate that the sediments were deposited rapidly, little time being given for that complete sifting of fine from coarse debris which is characteristic of the work of waves upon an open beach. These considerations lead to the inference that most of the Algonkian system in the Wasatch region is a product of deposition on land rather than in the sea, by means of rivers rather than in lakes or by winds, and at a geologically rapid rather than at a slow rate.

The existence of tension cracks is already referred to as indicating seasons of relative dryness. The dearth of black, gray, and olive green sediments and the prevalence of red, purple, and brown colors in the greater part of the section may also be interpreted to mean that the sediments were laid down under conditions which were oxidizing rather than deoxidizing. This in turn points to a scarcity of vegetation and to a relatively warm, dry climate during most of the year. The absence of fossils would be readily explainable upon this hypothesis, even if the formation were not so old as to have preceded the existence of preservable organisms.

In this connection attention may be called to the fact that many of the features of the Wasatch Algonkian have been observed in strata probably of the same age in the Grand Canyon region on the south, and in Idaho, Montana, and Canada on the north. Whatever interpretation applies to the one should apply to the homologous parts of the others, indicating that the conditions which favored such deposits were widespread in the West at the time. Barrell[17] argues for the continental origin of a large

[16] Joseph Barrell: Geological importance of sedimentation. Journal of Geology, vol. xiv, 1906, p. 552.

[17] Op. cit., pp. 553-568.

part of the Belt and Grand Canyon terranes, basing his interpretation on their physical characteristics. If all of these formations were in fact deposited chiefly by rivers on extensive plains in a climate which was semi-arid, or at least subject to dry seasons, it becomes much easier to explain the great scarcity of fossils throughout all of these essentially unaltered sediments, and also accounts for the fact that the few fossils which have been found are apparently Discinoids and Eurypterids, such as are commonly found in younger rocks not of strictly marine origin.

THE OGDEN QUARTZITE ELIMINATED

In Ogden Canyon two thick beds of quartzite appear to be separated by several hundred feet of shale and limestone. The geologists of the Survey of the 40th Parallel considered the lower of these to be Cambrian. The upper formation was named the "Ogden quartzite," and its age was thought to be approximately Devonian. This classification stood unchallenged for more than a generation. A few years ago Weeks[18] found Ordovician fossils in a quartzite and shale formation north of Brigham. This quartzite was separated from the Cambrian quartzite by a thick series of shale and limestone, and on this account Weeks considered it the equivalent of the "Ogden quartzite."

Contrary to this early view, the "Ogden quartzite" in Ogden Canyon is now believed to be merely a slab of the Cambrian quartzite repeated in this place by an overthrust. It is in fact twice repeated, but an observer traversing only the bottom of the canyon would see only a single repetition, as indicated in the structure section (see figure 6). The existence of these overthrusts is demonstrable, and the proof rests on more than one kind of evidence. From the rim of the canyon, either north or south, the structure can be seen as plainly as in a diagram (see plate 39, figure 1. The beds beneath the overthrust are much contorted, and the succession above the "Ogden quartzite" is identical with the succession above the Cambrian quartzite. A careful search even revealed Middle Cambrian fossils characteristic of Walcott's *Pioche shale* just above each of the three layers of quartzite in the canyon. Finally, the overthrusts which are responsible for these repetitions were traced horizontally 10 to 20 miles. They cut diagonally across the formations beneath and in details give ample additional proof of the structural conditions described.

In this connection it is well to note that an early Paleozoic quartzite formerly correlated with the "Ogden quartzite" is widely distributed in

[18] F. B. Weeks: Unpublished report to the U. S. Geological Survey, 1908.

the Wasatch Mountains. It is now bereft of its name, since the typical "Ogden quartzite" must be ruled out. As it is clearly exposed and well marked by fossils east and north of Geneva, it will be called the "quartzite at Geneva." This formation seems to be best exposed in the northern part of the Wasatch range (see plate 37, figure 1). It is a cream-colored calcareous quartzite interbedded with green shale near the top and bottom and altogether not over 400 feet thick. It is doubtless in this quartzite that Weeks found Ordovician fossils. The same fauna, found by the writer at two points near Geneva in 1909, includes the following fossils, as tentatively determined by Mr. E. O. Ulrich:

Orthis sp.	*Bathyrus ? congeneris*
Hebertella sp.	*Bathyrellus* sp.
Macronotella n. sp.	*Bathyrellus* cf. *fraternus* Billings
Leperditella n. sp.	*Symphysurus* (?) *goldfussi* Walcott
Primitella n. sp.	

Although most of the species in this list are as yet unnamed, they are correlated by Mr. Ulrich with the fauna of the upper part of the Pogonip limestone of Nevada and the later Beekmantown (early Ordovician) horizon of the Eastern States.

On the west slope of Mount Morgan, northeast of the town of that name, a corresponding thin quartzite member interrupts the monotonous succession of Paleozoic limestones. In the well known locality in Big Cottonwood Canyon, southeast of Salt Lake City, there appears to be a white quartzite somewhere in the middle of the Paleozoic succession and beneath the thick Mississippian limestone. Its outcrops, however, are badly obscured by soil and brush, and there are igneous intrusions in its vicinity. For this reason its relations and age have not been closely determined.

THE SILURIAN AND DEVONIAN LIMESTONES

Kindle[19] has recently shown that the Jefferson limestone of Montana, with a sufficient Devonian fauna, extends southward into the mountains of Utah, and he has traced it along the east side of Cache Valley, in the Bear River range. He has also identified in the same locality a limestone containing Silurian fossils conformable beneath the Jefferson formation. It was to be expected that the same formations would soon be found also on the west side of Cache Valley, in the Wasatch range proper. As exposed on the crest of the range, there is, between the Ordovician quartzite and the identifiable part of the Mississippian limestone, a succession of dark limestones, with some ash gray brittle dolomites having a thickness

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[19] E. M. Kindle: Bulletin of American Paleontology, no. 20, Ithaca, N. Y., 1908.

of 1,000 to 1,500 feet. In the lowest beds there are corals such as *Halysites* and *Favosites.* At a slightly higher horizon there are abundant shells, which Kindle thinks are the same as his Pentamerus fauna of the Bear River range. All the specimens, however, are poorly preserved, and show best upon the weathered surfaces. Between the Silurian horizon and the fossiliferous Mississippian there is a thick, dark limestone which corresponds satisfactorily with Kindle's Devonian Jefferson formation east of Cache Valley. Further search may be expected to reveal the Jefferson fauna in these beds.

Farther south the formations have not been identified by fossils, but beds lithologically similar, and lying conformably between the Ordovician and the Mississippian limestones, have been found near the summit of Mount Morgan. These are probably of Silurian and Devonian age. In the main range, near Ogden, the absence of this portion of the Paleozoic group is apparently due to the overthrusts which cut out the Middle Paleozoic portion of the succession.

A NON-MARINE MEMBER IN THE MISSISSIPPIAN LIMESTONE

One of the best sections of the limestones which represent the Mississippian (Lower Carboniferous) period in Utah has been overlooked until now. It is exposed around the sources of the south fork of Ogden River. The system can there be divided into three formations: An upper and lower limestone, with a middle shale. The upper formation is a succession of dark limestones rich in fossils, which have been determined by Dr. G. H. Girty as middle to late Mississippian in age. The lower limestones are chiefly dolomitic and devoid of fossils. The formation between these comprises a series of reddish or pinkish beds in which shales and thin-bedded limestones predominate. This middle formation has special characteristics which may be noted here.

The shaly formation is separated from the limestone beneath by an obscure unconformity, marked by sandy breccia containing pieces of the subjacent limestone. Above, however, it intergrades with the purely marine limestone of the Upper Mississippian formation. The total thickness is about 250 feet.

The origin of these strata appears to have been continental rather than marine. This conclusion is supported by a variety of evidence. A suggestive fact is that no fossils were found even in the calcareous layers and in sections which are well exposed. Near the base of the formation there are many layers of lavender and maroon shale, with abundant suncracks. The individual cracks are filled with a mixture of mud and sand. Sparsely dotted over the surfaces of the shales and also upon thin layers of limestone, there are pitted and frosted sand grains. It is suggested that these isolated grains were dropped by the wind on soft mud at a time when it was temporarily exposed to the air. Interbedded with some of the sun-cracked strata there are argillaceous breccias in which the angular fragments are chips of hardened mud. These may well be broken pieces of the curled plates which are usually produced in the making of tension cracks in mud. On some of the layers of muddy limestone there are impressions of the faces and corners of cubes, which may be ascribed to the temporary formation of salt crystals which were later dissolved.

The precise mode of deposition of such a deposit is open to question. The facts above stated seem to imply that the sediments were deposited in shallow-water bodies and streams on land. The requisite conditions are probably supplied today on the surfaces of large deltas of flat gradient in regions which are either generally or seasonally arid.

These Mississippian shales seem to have a fairly wide distribution in the Wasatch Mountains. They are represented in Ogden Canyon by physically similar beds, in which the red color is largely replaced by buff and gray. In that locality one of the beds has also yielded a few brachiopods and jointed fucoidal fossils of problematical nature.

On the west slope of Mount Morgan reddish shales with mud breccias were noted in the Mississippian succession. There seems to be a representative also along the crest of the Wasatch range southwest of Wellsville.

THE RED BEDS NEAR MORGAN

In the upper canyon of Weber River the conspicuous Weber quartzite is separated from the dark Mississippian limestones by a formation of red sandstone and shale with intercalated thin limestones, having a total thickness of about 500 to 2,000 feet. This formation was noted by the geologists of the Survey of the 40th Parallel, but not named. Weeks, in an unpublished manuscript on the geology of northeastern Utah and adjacent regions, calls it the "Morgan formation," and in the present paper that name is adopted. The prevailing rock in the Morgan formation is earthy sandstone, which is relatively soft. Fresh surfaces are generally white or pink, but on exposure the rock turns brick red. Some beds are distinctly shaly, and here and there thin layers of gray limestone with a few fossils are interbedded with the series. The Morgan formation passes upward through alternate gray shales, limestones, and sandstones into the more or less calcareous base of the Weber quartzite. In this transitional zone there are a few fossils—chiefly Lingulas and Discinoids. The lower limit of the formation is sharp, for the earthy red sandstones rest upon a cavernous weathered surface of fossiliferous gray limestone. Just above the contact lies a coarse sandstone which consists of well rounded frosted sand grains bound in a deep red matrix and including bits of limestone and black chert from the underlying series. Although the bedding of the Morgan formation is essentially parallel to that of the limestone below, the relations here clearly indicate an unconformity, signifying an erosion epoch between the Mississippian and the Pennsylvanian.[20]

In two small lots of fossils from the beds of limestone immediately below the unconformity, Dr. G. H. Girty has identified the following species:

Campophyllum ? sp.	*Spirifer boonensis ?*
Glossina nebraskensis	*Spirifer cameratus ?*
Producta cora	*Spirifer kentuckyensis ?*
Productus semireticulatus var. *hermosanus*	*Composita subtilita*
Productus nebraskensis	*Hustedia mormoni*

Two other lots, one of them from a thin limestone within the Morgan formation, and the other from transition beds at the top, yielded the following:

Monilipora prosseri	*Productus cora*
Zaphrentis gibsoni ?	*Productus gallatinensis*
Glossina nebraskensis ?	*Spirifer rockymontanus*
Lingulidiscina utahensis	*Composita subtilita*
Productus nebraskensis	*Cliothyridina orbicularis*

It is obvious that these faunules are very closely related to each other, and Girty assigns them all to the early part of the Pennsylvania period. It appears, therefore, that although the contact features show an unconformity at the base of the Morgan formation, the erosion interval must have been geologically brief.

The red beds have been traced from Weber Canyon northward 5 or 6 miles to the point where they disappear beneath the Eocene strata. As it has not been recognized in other parts of the region, the formation is probably local in extent.

THE DISAPPEARANCE OF THE WEBER QUARTZITE

In the canyon of the Weber River, just above the town of Morgan, the geologists of the Survey of the 40th Parallel found a great quartzite for-

[20] It may be mentioned here that Berkey finds evidence of a well marked unconformity above the Mississippian limestone on the southern flank of the Uinta Mountains (Bulletin of the Geological Society of America, vol. 16, pp. 517-530. Stratigraphy of the Uinta Mountains, 1905). His findings are questioned by Emmons (Bulletin of the Geological Society of America, vol. 18, 1907, pp. 287-302) and Boutwell (op. cit.).

mation of Pennsylvanian age to which they gave the name "Weber quartzite." According to the original measurements the formation is 5,000 to 6,000[21] feet thick. A similar quartzite has been found in the Park City district to the south and in Big Cottonwood Canyon, southeast of Salt Lake City, but it has not been identified from Ogden River northward, so far as the writer can learn.

Last summer the writer traced the outcrop of the quartzite northward from the type locality, and in doing so found that it grows thinner and finally disappears about 7 miles north of Weber River. If the Paleozoic formations were fully exposed in this locality, the interpretation of this disappearance would be comparatively easy; but the facts are obscured, because the Eocene deposits come in from the east and cover all of the beds above the Weber quartzite at the point where the latter disappears. However, it is significant that when the Pennsylvanian strata do reappear 4 to 5 miles farther northwest, the Weber quartzite is missing, and the Pennsylvanian phosphatic series[22] (the Park City formation of Boutwell) rests directly on the Mississippian limestone. The structure is simple and outcrops are sufficiently good, so that faulting can not be appealed to in this region. In all other sections observed from here north and northwest the same relation holds.

Farther northeast, on the eastern slope of the Bear Lake valley, Gale[23] has found the Weber quartzite generally present, but varying considerably in thickness.

A closer examination of the sequence shows also that the sandy beds which mark the base of the Park City formation rest not on one, but on several members of the Mississippian system, as shown in the accompanying sections. The shale and limestone member at the top of first and fourth are missing in the other sections. These beds are peculiar, because the shales are purple and the limestone nodules bright green mottled with red, and in addition they are richly fossiliferous. For these reasons the strata are not likely to be overlooked. Furthermore, the fauna in these beds is correlated by Girty with the Kaskaskia fauna of the Central States, and therefore may be supposed to be older than the fauna at the top of the Mississippian limestone in Weber Canyon, which Girty refers to the early Pennsylvanian. Unfortunately, in these sections the exact contact was not visible, and for that reason the evidence loses some of its cogency.

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[21] To the writer these measurements seem excessive; but as he has made no exact observations to test their accuracy, he can only register a doubt.

[22] The Carboniferous beds are described in the writer's paper, "Phosphate deposits near Ogden, Utah." U. S. Geological Survey, Bulletin 430, Contributions to Economic Geology, 1909.

[23] Hoyt S. Gale: Personal communication.

Taken together, these facts of distribution and relation are suggestive of an unconformity truncating the Weber quartzite and Morgan formations and going down into the Mississippian limestone.

Further light on this question is furnished by the contact relations between the Weber and Park City formations. In Weber Canyon and several adjacent localities this contact is fairly well exposed. The excellent section in Tunnel Hollow may be taken as typical. There the black shale and limestone of the Park City formation grades downward into alternate reddish sandstone, lavender and buff calcareous shales, and finally into soft, massive white sandstone, with small concretions of limonite. At the base of this white sandstone there is found nearly everywhere a hard quartzitic breccia which contains angular fragments of

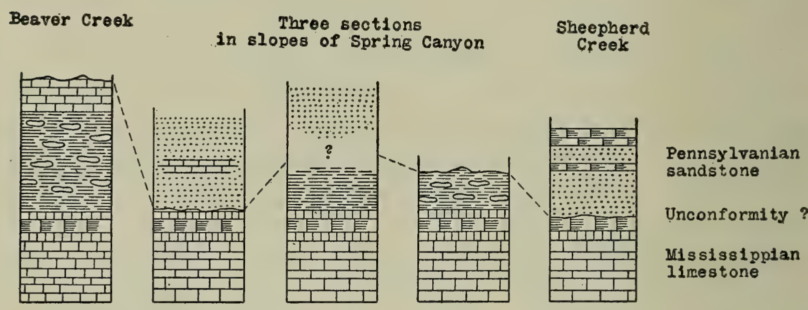


FIGURE 3.—*Sections of the mid-Carboniferous Strata in the upper Valley of Ogden River*

Showing variation in the horizon of the Pennsylvanian sandstone. The shale with nodules contains the late Mississippian fossils

white chert, gray quartzite, and black chert, in the order given. One chert fragment proved to be a worn specimen of a horn-coral, silicified. This breccia rests with slightly undulating contact upon pale gray quartzite, which is continuous with the body of the Weber quartzite. The contact slowly truncates the individual layers of the quartzite below. On the contact surface there is no accumulation of soil or the products of weathering; it is swept clean. Here and there, however, open fissures in the quartzite are filled with wedges of the chert breccia.

At another exposure of the contact, just west of Robison's ranch, the breccia is thicker and contains some water-worn material and a few boulders as much as 15 inches in diameter. There, also, fragments of quartzite clearly predominate over the other constituents.

In Big Cottonwood Canyon, near Salt Like City, the writer measured somewhat roughly a section just north of the Wasatch Planting Station of the Forest Service, in the upper part of the canyon. In this section the Weber quartzite is easily recognized, but seems to be reduced to a thickness of 1,200 to 1,500 feet. The exact contact between the quartzite and the Park City formation is unfortunately covered with soil. At about the proper horizon, however, there are poor exposures of a soft, white, fine-grained sandstone like that in Weber Canyon, and it likewise contains angular fragments of gray quartzite and chert.

The observable facts with reference to this contact leave much to be desired, and no attempt is made here to interpret fully the conditions under which it was made. Certain things, however, seem to be clear: (*a*) The Weber quartzite is limited above by an irregular eroded surface, which is not exactly parallel to the bedding; (*b*) it was subject to disintegration, and (*c*) not merely one, but a variety of beds in the formation were exposed, as is shown by the large amount of chert as well as quartzite in the breccia. On the whole, the evidence for the existence of an unconformity at this horizon seems to be conclusive.

The importance of the unconformity is uncertain. If the Weber quartzite is a formation of only local extent, and if some of the more calcareous beds farther north were deposited contemporaneously, then the observed unconformity may in fact be due to a slight erosion of the surface of the formation and should represent but a brief land interval. If, however, the Weber quartzite was once far more extensive than now, and if it has been removed from the northern part of the Wasatch region, and elsewhere reduced to a varying thickness by erosion within the Pennsylvanian period, then this interval must have been relatively long. It is significant in this connection that the fragments of quartzite in the basal breccia were quartzite, rather than sandstone, when broken from the parent ledge during the erosion interval, as is shown by the preservation of sharp corners and edges. For the present the problem must remain in this doubtful state, but careful observations at as many points as possible, within a radius of 100 miles or more, should soon decide it.

Structure

PREVIOUS STUDIES

The interpretation of Wasatch structure which has prevailed until recent years is that derived from the work of the Survey of the 40th Parallel[24] According to this view, the main range is a monocline dipping eastward and cut off on the west by a profound normal or gravity fault. Small transverse normal faults with a general east-west trend served to account for sudden shiftings of outcrops. In addition, mention was

[24] Op. cit., vol. ii, sections 3 and 4.

made of closed recumbent folds here and there, generally confined to the weaker members of the series and well shown in Ogden Canyon.

The only important modification of this view seems to be that furnished by Boutwell in 1907, on the basis of his studies in the Park City mining district.[25] The most important feature found there is an overthrust fault of large displacement, the first to be reported from the Wasatch Mountains.

OVERTHRUSTS IN THE VICINITY OF OGDEN

In 1909 the field observations confirmed the earlier interpretation of the main range from Brigham northward. That portion of it is apparently an uninterrupted monocline with occasional little transverse faults. Furthermore, there appeared to be nothing severely inconsistent with the view that the west front of the range is a normal fault-scarp, as generally supposed. From Willard south to Weber River, however, the structure

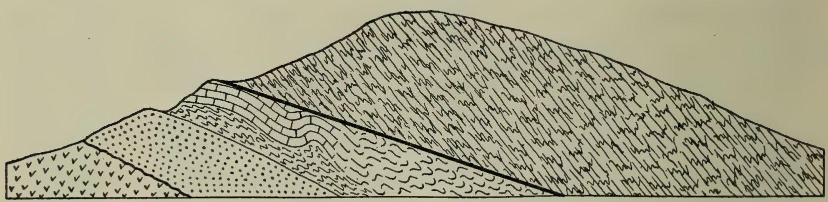


FIGURE 4.—*Generalized Section of the Wasatch Range at Willard, Utah*

Showing Algonkian slaty series overthrust on middle Cambrian limestone

is much more complex. It may be described in general as a shingled structure with overthrust slabs or wedges dipping eastward. The weaker members of these slabs, especially near the overthrust planes, have been bent into compressed recumbent folds and in detail are much contorted, At least three of the overthrusts are large enough to deserve separate description, and there are also several small thrusts which modify the outcrops and structures in important details. Why these overthrusts were localized near Ogden is a question which will require for solution a broader acquaintance with the larger structures in northern Utah than is now available.

The greatest of the overthrusts may well be considered the master structural feature of the northern part of the range (see figure 5). It rises from beneath the Salt Lake sediments just north of the village of Willard, crosses the lower part of Willard Canyon, and rises gradually along the western buttresses until it reaches the crest of the range just

[25] Op. cit.

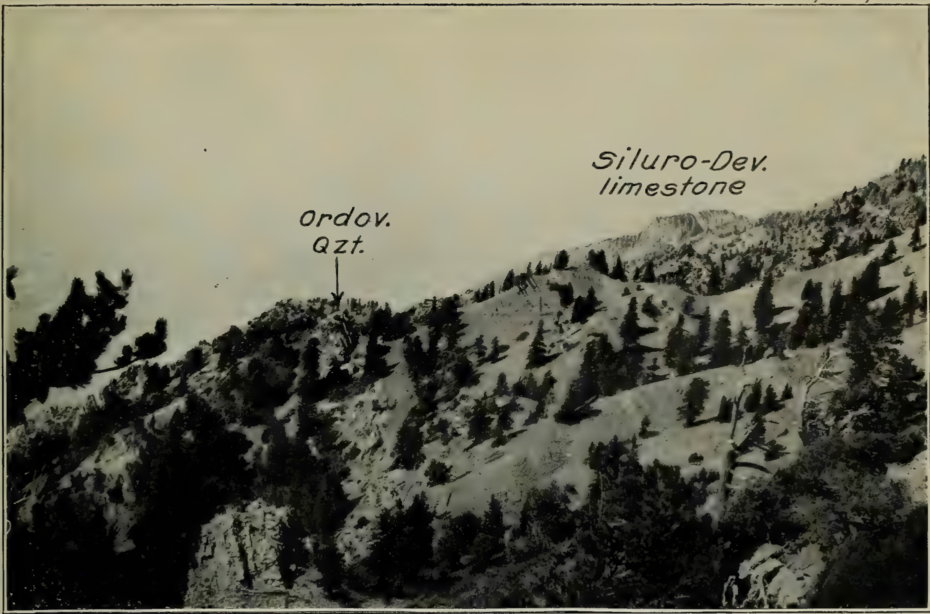


FIGURE 1.—CONFORMABLE SEQUENCE FROM LEFT TO RIGHT OF ORDOVICIAN, SILURIAN, AND DEVONIAN STRATA, UPTURNED ALONG THE WESTERN SLOPE OF THE WASATCH RANGE, SOUTHEAST OF WELLSVILLE

The early Ordovician quartzite forms salient reefs

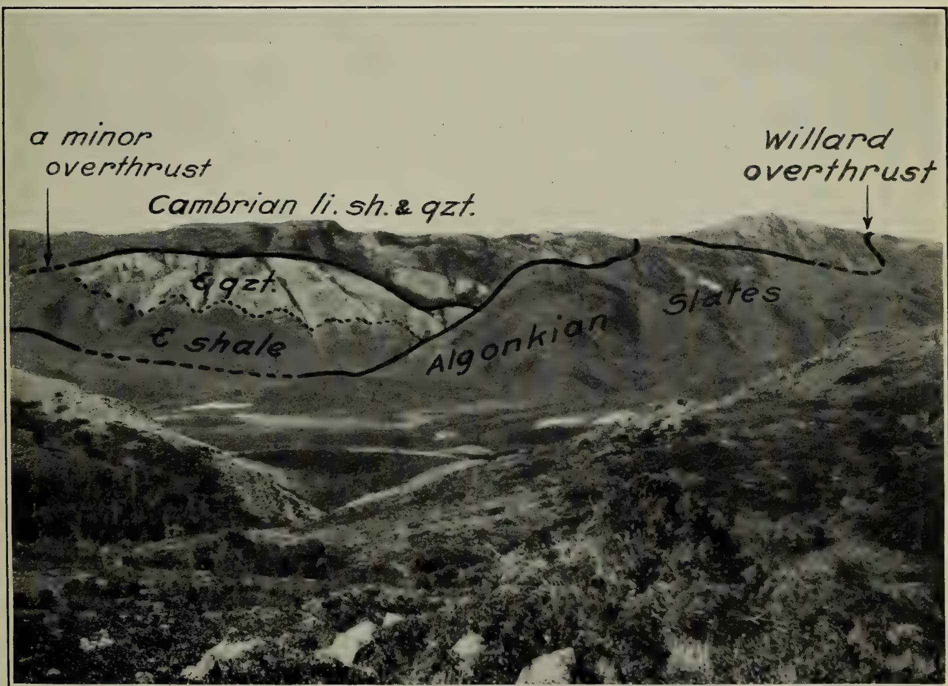


FIGURE 2.—EASTERN SLOPE OF THE WASATCH RANGE OPPOSITE HOT SPRINGS

GEOLOGIC EXPOSURES ON THE EASTERN AND WESTERN SLOPES OF THE WASATCH RANGE

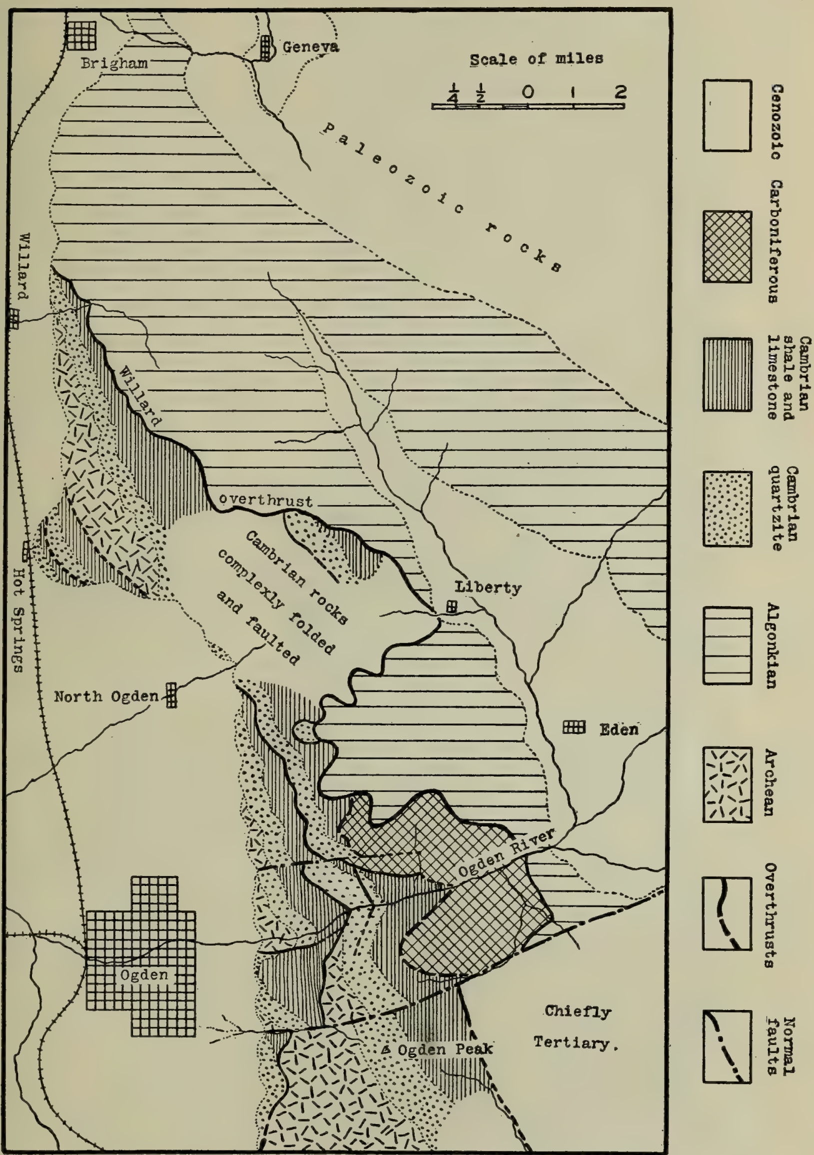


FIGURE 5.—*Geologic Sketch Map of the Vicinity of Ogden, showing Overthrusts and normal Faults*

north of Ben Lomond Peak ("Willard Peak" of the 40th Parallel Survey maps); thence it passes diagonally down the eastern slope, is temporarily concealed by wash along the east base near the little village of Liberty, but rises again at a low angle into the summits of the spurs northeast of Ogden. It crosses Ogden Canyon near the east end and continues southward along the eastern slope of the range. Presently its outcrop is shifted by the Huntsville fault westward to the base of Ogden Peak; thence it soon disappears beneath Tertiary and later sediments in the Morgan basin. The overthrust has not been traced farther south, but it can be confidently predicted that a structure of such magnitude must continue many miles before it dies out in that direction. Along this great thrust-plane the Lower Algonkian formations, consisting chiefly of slate and graywacke, with some quartzite, have been pushed up over Paleozoic rocks. The maximum horizontal displacement is about 4 miles, so far as exposed, but this is probably but a small fraction of its total displacement. The inclination of the thrust-plane varies considerably

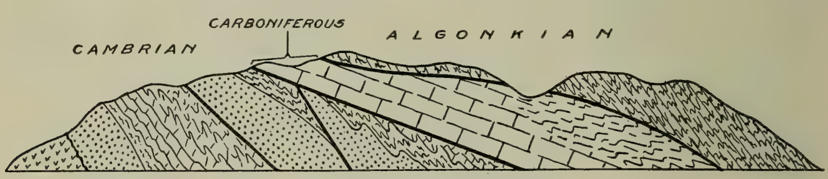
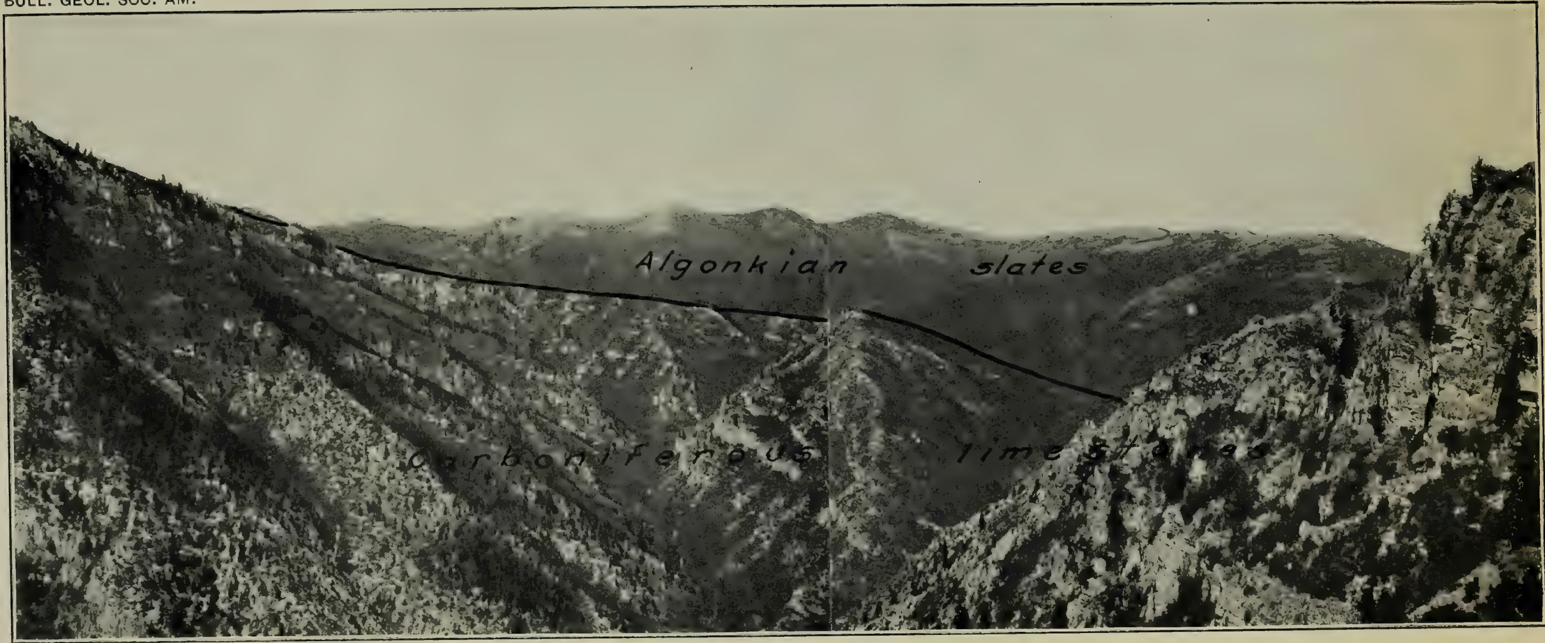


FIGURE 6.—*Diagrammatic Structure Section of the Wasatch Range, in Ogden Canyon*
Showing the succession of overthrust slabs of Paleozoic and Proterozoic strata

from point to point. Locally it is as high as 50 degrees, but in the mountains northeast of Ogden it averages about 15 degrees. This has suggested that the thrust-plane may have been folded at a later date, like those of the southern Appalachians. Inasmuch as the overlying Eocene beds are slightly folded in northern Utah, it is safe to say that the thrust-plane has also been flexed to the same degree; but it is equally probable that the overthrust was originally an undulating rather than a plane fracture. This fracture is clearly exposed in Willard Canyon and is there the only overthrust. It may therefore be called the *Willard* thrust.

In Ogden Canyon there are two other large overthrusts, but both are of distinctly less magnitude than the great Willard thrust—if, indeed, they are not actually branches of it. One of these has already been mentioned in connection with the hypothetical "Ogden" quartzite. This overthrust arises from the Salt Lake plain east of the village of North Ogden, mounts along the frontal spurs of the range, and then descends into Ogden Canyon (see figure 5). Throughout this part of its course



WILLARD OVERTHRUST, OGDEN CANYON, UTAH

As seen looking northwest from the rim of the canyon

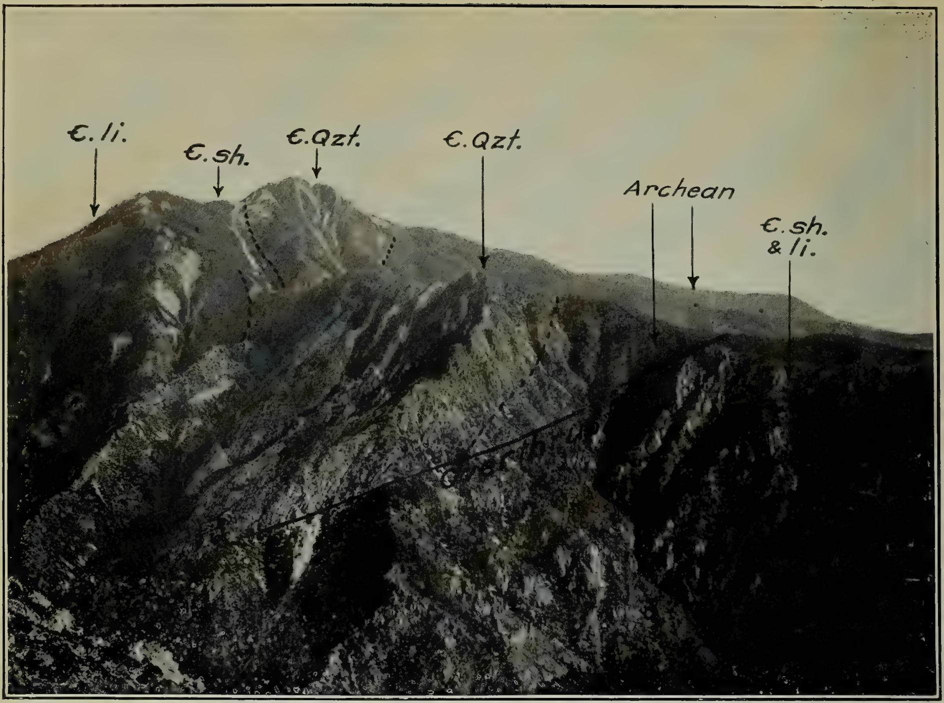


FIGURE 1.—OGDEN PEAK AND THE SOUTH SIDE OF OGDEN CANYON, FROM THE NORTHWEST
Shows the Ogden overthrust

FIGURE 2.—WEST FRONT OF THE WASATCH RANGE AT OGDEN
Ogden Canyon and Ogden Peak are visible to the right of the middle. Compare figure 7

VIEWS OF OGDEN PEAK AND OGDEN CANYON, AND THE WASATCH RANGE, UTAH a thick slab of the Cambrian quartzite lies above the thrust-plane, and the Middle Cambrian limestones are beneath it. That the thrust-plane is not confined to a particular horizon is shown by two facts: (*a*) The underlying limestone is but 200 to 300 feet thick at one point on the front of the range, but is nearly 2,500 feet thick along the bottom of the canyon, and (*b*) the overlying quartzite is but a few hundred feet thick east of North Ogden, but is complete, and even carries a wedge of Archean gneiss beneath it in Ogden Peak.[26] The weak, shaly Middle Cambrian limestones just below the overthrust are intensely folded, the folds being mashed flat parallel to the general bedding. Thinning on the limbs and thickening on the crests of the folds are conspicuous. Only suggestions of such structures can be seen in the limited exposures along

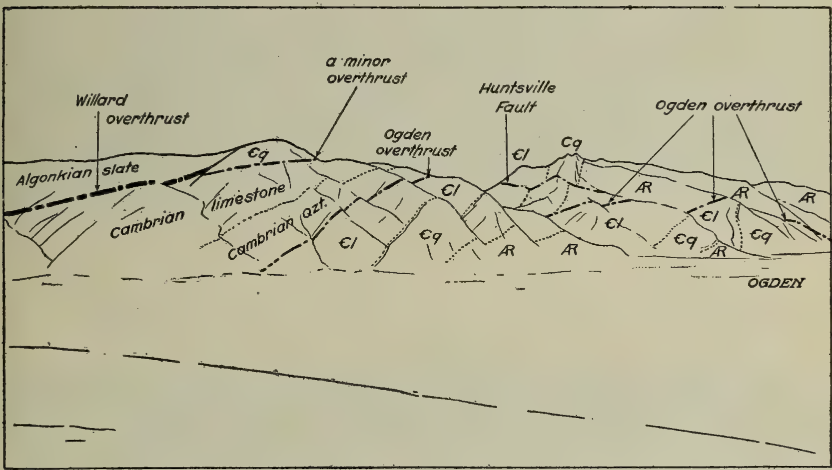


FIGURE 7.—*Diagram to the Geology and Structure within the Scope of Figure 2, Plate 39*

the bottom of the canyon, but they are in plain view from the south rim of the valley. From Ogden Canyon this overthrust runs south along the front of the range, bringing Archean gneiss out upon the Cambrian limestone. It sinks again into the Salt Lake plain before reaching Weber River.

It may be said in passing that there is a smaller, but nevertheless important, overthrust near the top of the quartzite formerly called the "Ogden." A sliver of the quartzite with the overlying shale and limestone has overridden the Middle Cambrian shale with a little of the limestone, thus making a second repetition of those beds. It does not reach

[26] To the people of this region Ogden Peak is known as "Observatory Mountain."

the crest of the spurs on either side, because it is cut off by the structure next to be described (see figure 6).

The third prominent overthrust crosses Ogden Canyon in the vicinity of the Hermitage. It is noteworthy because it reverses the order of strata which characterizes most overthrusts, namely, older upon younger.

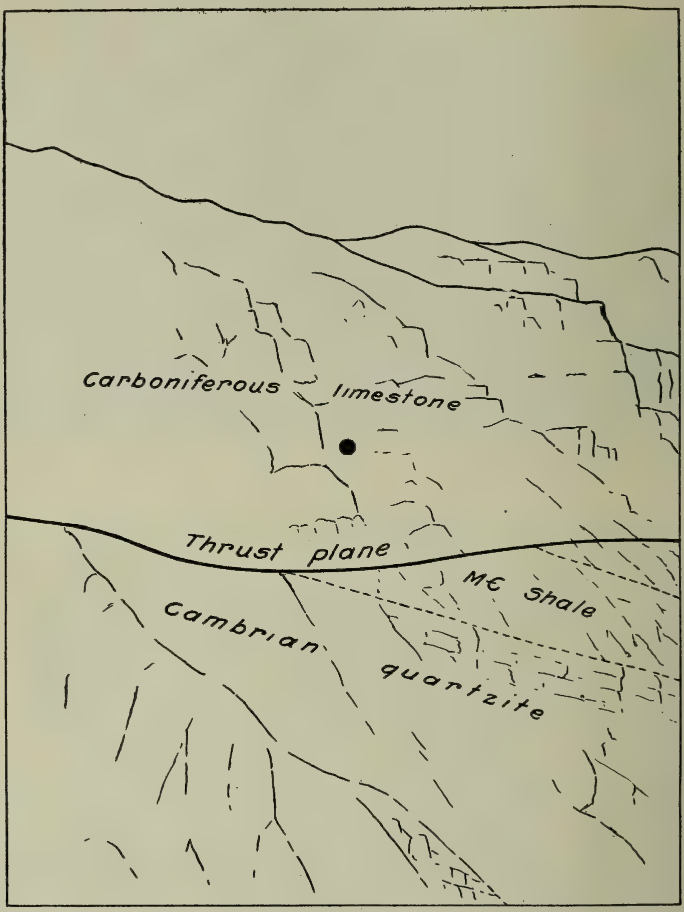


FIGURE 8.—*Diagram of Overthrust shown in Figure 2, Plate 40*

Along this fracture the thick-bedded massive Mississippian limestone seems to have been pushed at a low angle out over the lower beds of the series. The overthrust cuts out not only part of the Middle Paleozoic sequence, but even one of the two repeated slabs of the Cambrian, so that the Carboniferous strata come to rest upon the middle body of the Cam-

FIGURE 1.—Z-SHAPED FOLDS IN THE CARBONIFEROUS LIMESTONE BENEATH THE WILLARD OVERTHRUST, NEAR THE EAST END OF OGDEN CANYON

FIGURE 2.—DETAIL OF THE NORTH WALL OF OGDEN CANYON, SHOWING THE MASSIVE CARBONIFEROUS LIMESTONE OVERTHRUST FROM THE RIGHT UPON CAMBRIAN QUARTZITE, SHALE, AND LIMESTONE (SEE FIGURE 8)

EXPOSURES OF CARBONIFEROUS LIMESTONE, OGDEN CANYON, UTAH

brian limestone. Beneath the fault the thin-bedded limestone and shale are bent into recumbent folds which were noted by Hague and Emmons in their first visit to the canyon, about 1870. In fact we can not read their description[27] of this canyon without perceiving that they recorded the essential features of this overthrust without recognizing it as such. Since this fault lies almost entirely within the thick succession of Paleozoic limestones, its exact course is difficult to trace without detailed study. It is cut off both north and south of Ogden Canyon by the overlapping of the great Willard thrust.

Northeast of the village of North Ogden, also, there are several subordinate yet important thrust-planes beneath the dominant overthrust first described. Some of the overthrusts in Ogden Canyon have been traced into this locality. Others can probably be extended in the same way when more detailed work is done. It is clear that there are also several small overthrusts which do not appear in the Ogden region. The front of the Wasatch Range near North Ogden has indeed a highly complex structure, in which overthrusts and recumbent folds are the characteristic features. Even in the low plateau-like extension of Paleozoic rocks near Hot Springs the rocks are much disturbed in detail and the faults appear to be overthrusts.

So far as present information goes, the overthrusts seem to be confined to that part of the Wasatch range which lies south of Brigham. There can be little doubt that the overthrusts were made at the same time that the Paleozoic rocks were folded; and that disturbance is generally assigned to the close of the Cretaceous period. It seems to be a fact that the Lower Eocene (Wasatch) sediments cover the outcrops of the overthrusts in several places, thus indicating that the folded and overthrust structures had been deeply eroded before the Eocene period was far advanced.

TRANSVERSE FAULTS

In the reports of the Survey of the 40th Parallel several faults with general east-west trend are postulated to explain abrupt changes in the Paleozoic outcrops. Of these, the one about a mile north of Ogden Canyon was identified and traced by the present writer. The one in North Ogden Canyon was not found, and the structure there seems to be explained more readily as folding, without any assumption of faulting.

East of the city of Ogden, in a small valley now locally known as "Waterfall Canyon," there is another fault which appears to be of the normal type and which is described in the report of the Survey of the

[27] U. S. Geological Exploration of the 40th Parallel, vol. ii, p. 400.

40th Parallel.[28] At the west base of the range the Middle Cambrian limestone abuts against the Archean complex a few hundred feet below the base of the Cambrian quartzite. The stratigraphic displacement in the vertical plane therefore amounts to but little over 2,000 feet. From this point the fault-plane was traced eastward several miles, and its course is inferred (although not observable) for a distance of 15 to 20 miles. It crosses the two north spurs of Ogden Peak, shifting the outcrops to the west on the south side, and at the east base of the peak cuts

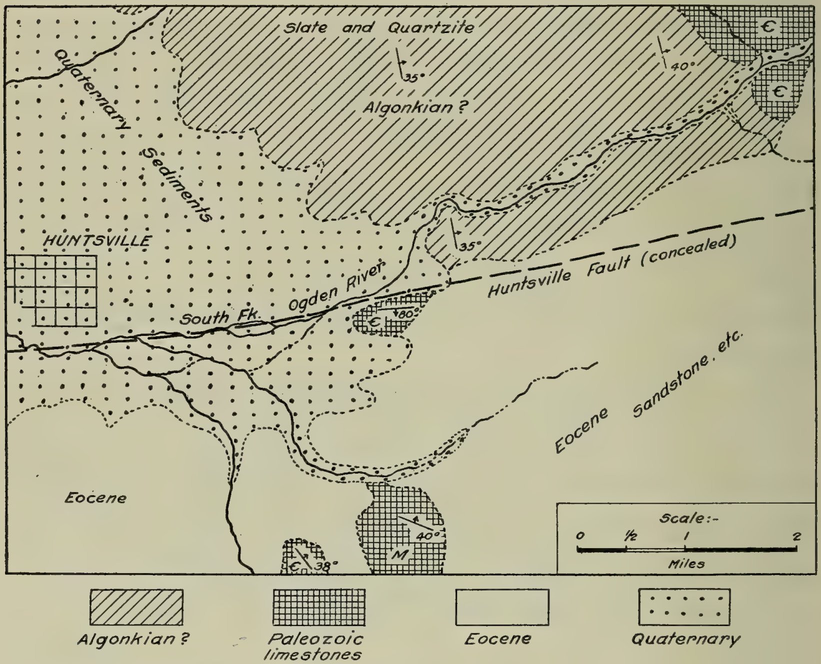


FIGURE 9.—*Sketch Map of Part of Huntsville Basin and adjacent Bear River Plateau*

Showing field evidence of the extension of the Huntsville fault

the Willard thrust. Thus the outcrop of the low dipping overthrust is shifted westward on the south side a distance of 2¼ miles. The soft Algonkian slates above the overthrust have offered little resistance to erosion, and to this fact is due the low, hilly region immediately east of Ogden Peak. The fault continues under the Pleistocene sediments of the Huntsville basin, and may therefore be named *the Huntsville fault.* That it continues much farther east, and with increasing displacement, is indicated by the relations of the outcrops in the southern continuation of the

[28] U. S. Geological Exploration of the 40th Parallel, vol. ii, pp. 394-395.

Bear River plateau, 4 to 8 miles east of Huntsville. There the great series of Algonkian quartzite and slate with the overlying Cambrian beds is suddenly cut off, and immediately in the line of strike there is an exposure of Middle Cambrian fossiliferous limestone with east-west strike and vertical or variable dips. The fault doubtless passes between these outcrops. This fault is of the type usually called "normal"—that is, it is nearly vertical and dips toward the down-thrown side.

Presumably the direction of displacement along this plane had a large vertical component, but the precise direction has not been ascertained. The greatest shifting of outcrops amounts to about 3½ miles in the hills east of Huntsville. A horizontal displacement of such dimensions would involve changes of volume on one side or the other on a scale which seems impossible. With the observed dips, a vertical displacement of about 12,000 feet would seem to be required to explain the shifting of the outcrops. If the movement was diagonal, the amount of displacement would be still different, but in any case the facts indicate a fault of large dimensions.

The transverse faults, including the Huntsville fracture, no longer have any topographic expression, except that which is due to the relative resistance of the rocks on one side or the other. The scarps have been wholly removed by erosion. From this fact it seems probable that they are older than Quaternary or even than late Tertiary. Their age can be fixed more definitely in the future by a careful study of the relation of the Eocene beds to the fault. From certain meager observations the writer expects that the faults will be found to have cut the Wasatch sediments (Lower Eocene).[29]

QUATERNARY FAULTING

The evidence that the front of the Wasatch range is a great fault-scarp or series of scarps, of comparatively recent date geologically, has been ably discussed by Gilbert, Davis, and others. The important evidence is almost wholly physiographic. The question was given only casual attention last summer, and such observations as were made do not appear to conflict with the current interpretation.

Conclusions

The chief conclusions presented in this paper are these:

(*a*) The Cambrian system has a basal quartzite of moderate and tolerably uniform thickness, and this is separated by a traceable unconformity

[29] Vermilion Creek formation of the 40th Parallel Survey.

from an older and very thick series of quartzite and slate which is presumably of Algonkian age.

(*b*) The exposed Algonkian series is probably not marine, but of continental origin, like the similar formations in Arizona and Montana.

(*c*) The Ogden quartzite, as originally defined, has no existence, but there is a thin quartzite of Ordovician age best exposed near Geneva.

(*d*) The Silurian system has been identified in the main Wasatch range by characteristic fossils, and the Devonian is doubtless present also.

(*e*) In the Mississippian system there is an interesting series of sun-cracked shales and peculiar limestones interpreted as a non-marine deposit.

(*f*) The Carboniferous red beds in Weber Canyon rest unconformably on the Mississippian limestone and are themselves probably of terrestrial origin.

(*g*) The Weber quartzite thins north of the type locality and quickly disappears. The fact is probably due to an unconformity between it and the overlying Park City phosphatic series, both of Pennsylvanian age.

(*h*) The current interpretation of the structure of the Wasatch range must be modified to include large overthrusts with accompanying small but intense folds and minor thrusts.

(*i*) A transverse fault of large dimensions in the latitude of Ogden has shifted the formations of the Wasatch and Bear River ranges laterally ½ to 3 miles.

(*j*) The overthrusts are of Cretaceo-Eocene age, while the normal faults are probably post-early Eocene.

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RELATIONS OF PRESENT PROFILES AND GEOLOGIC STRUCTURES IN DESERT RANGES[1]

BY CHARLES R. KEYES

(*Presented by title before the Society December 29, 1908*)

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INTRODUCTORY

Mountains of the so-called Basin-range type occur over a very much larger area of western America than is commonly supposed. They not only occupy the Great Basin country, but an expanse of territory ten times as vast. The desert ranges extend from the northern boundary ot the United States southward far into Mexico. Throughout this great area they preserve intact all of their distinctive characteristics: more or less complete isolation of the ranges, abrupt elevation above the surrounding plains, lofty heights, short lengths, simplicity of structure, and the very resistant nature of their rocks. There are many other equally distinctive features which are not so conspicuous.

[1] Manuscript received by the Secretary of the Society December 31, 1908.

In accounting for the origin of the mountains of the Desert region, it was long believed that they were formed by simple normal faulting on a grand scale. This was the view first advanced by Gilbert,[2] and it was generally adopted by the early explorers of the Great Basin region of western United States. At first glance this explanation appears to be quite sufficient. Throughout the arid region the mountains are largely devoid of vegetation and the attitude of the strata is readily made out even at great distances. Around the bases of the ranges long, smooth slopes extend in all directions until they merge into the central parts of the intermont plains. To all appearances the slopes are composed of debris washed down from the bordering highlands, and the natural inference is that the intermont valleys are constructional plains formed of the wash from the mountains on all sides. In many cases the so-called wash-plains extend up the mountain sides until the rugged bare rocks seem to be all but completely buried.

Within the past few years our notions regarding the origin and structure of the desert ranges have undergone some very radical changes. The tendency is to modify more or less the simple normal fault hypothesis so generally held a generation ago. There are some novel reasons for the recent awakening of a new interest in the genesis of this class of mountains. Prominent among these newer considerations is the idea that the dominant relief features of the so-called Basin-range type of mountains are probably not due so much to local and intense fault-movements as they are to the differential topographic effects of general desert-leveling, without notable assistance from running water, but with eolic influences operating to their maximum extent. On the local progress of eolation the ancient faultings and flexings have a very important influence, yet the rearing of the mountains throughout the region can not be ascribed wholly to a single cause. In some, and in perhaps most, cases the direct rôle of recent crustal movement seems quite secondary.

Subdivisions of the American Arid Region

As the term is usually employed, the desert region of the United States is a rather vaguely defined part of our country. Geographically the territory included within the limits of this region actually embraces several more or less well defined provinces of which the Great Basin is only a minor part. In the central portion of the region is the elevated plain or dome commonly called the Colorado plateau. Only to the north of

[2] Geographical and Geological Survey West of the 100th Meridian; Report of Progress for 1872, p. 48, 1874.

the Colorado plateau does the Great Basin, properly so called, extend. West and south of the high plateau is a centrally depressed plain studded thickly with typical desert ranges. It may be termed the Californian Gulf basin, and may be regarded as reaching down into the sea in the Gulf of California. East and south of the Colorado Plateau province is the northern extension of the Mexican tableland.

The proper discussion of Basin-range structures requires that the features of the four subregions should be considered separately. Each presents phases of the different structures so very distinctive that it effectually prevents advantageous generalizing for the entire desert country.

Explanations of the Origin of the Great Basin Ranges

The several views regarding the origin of the Basin ranges may be, according to the central feature emphasized, tabulated as follows:

1. Folding:
   - *Simple* and direct .... King, 1870.
2. Faulting:
   - *Simple* and direct .... Gilbert, 1874. Powell, 1876.
   - *Simple*, previous folding .... King, 1878. Russell, 1884. Diller, 1886. Le Conte, 1889.
   - *Simple*, previous folding and planing off .... Dutton, 1880.
   - *Compound*, and direct .... Lauterback, 1904.
3. Erosion:
   - *Corrasive*, folded and faulted ridges, complex .... Spurr, 1901.
   - *Corrasive*, faulted blocks .... Davis, 1903.
   - *Deflative*, flexed, faulted, and planed region, differentially eroded by wind action mainly .... Keyes, 1908.

In general the diversity of opinion here shown is, as a matter of fact, more apparent than real. The conclusions reached by different writers are, in the main, true for the localities in which the particular investigations were first carried on; they are not necessarily antagonistic to one another, but mutually supplementary. Any seeming shortcomings appear to be due rather to generalization too broad than to incomplete observation. King's first opinion admits of no other interpretation in northern Nevada, nor does it preclude later-date faulting, as suggested by Gilbert. The latter's grand conception seems plain in the Grand Canyon district, where displacement has been manifestly so vast and so recent that its expression in the surface relief has not had time to be entirely mastered by erosional effects. Lauterback's idea of a mountain-block and a valley-block no doubt holds good for a multitude of instances other than the few which he cites in northwestern Nevada. For a broad generalization its main qualifications are that the valley-block be also a block of soft rocks and that the time of faulting greatly antedate the present expression of relief. So, too, Davis' theory of extensive dissection of mountain masses is more directly applicable to the loftier mountain ranges, where there is notable approach to normal humid conditions of climate, while aridity prevails on the plains about. My own views have been that there is much greater complexity in the genesis of the desert ranges than is generally supposed; that while flexing and profound faulting have gone on rhythmically, perhaps ever since Jurassic times, the greater part of the crustal movements had already taken place before the extensive planing off in Tertiary times, and that the differential erosion of such an even surface composed of alternating belts of resistant and weak rocks have resulted in the marked contrasts of relief now exhibited by abrupt mountain and even plain, the extensive erosion being mainly eolic in character.

General Tectonics of the Desert Region

Singularly enough, controversy relating to the geologic structures of the Desert ranges has been confined almost wholly to a relatively minor portion of the arid region. The Great Basin, which is scarcely one-sixth of the whole, has received nearly all of the attention. Were it not for this fact, the generally accepted notions concerning desert tectonics and the rearing of the mountains would be no doubt quite different from what they now are. In their bearing on the general tectonic conceptions the geologic structures of the several provinces are equally as important and equally as illuminating as those of the Great Basin.

Strangely enough, the ideal type of Basin-range structure appears to be, so far as recent observations go, almost entirely wanting in the Great Basin district itself. Spurr's lately expressed views[3] regarding the mountain ranges of Nevada are without much question in the main correct, at least in so far as they relate to the rare occurrence of typical block-mountains. However, that these mountain ranges are formed chiefly by flexing of the strata, after the manner of the Appalachians, is a statement which must be substantiated by additional evidence before it can be accepted fully.

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[3] Bulletin of the Geological Society of America, vol. 12, 1901, p. 217.

Eliminating for the moment the mastering effects of general and local desert-leveling and confining the attention to tectonics alone, we find that there are discernible throughout the entire arid region two general and distinct systems of geologic structures. These are widely separated from each other in point of time. The younger of them may be regarded as mainly produced during the late Tertiary period, while the older may be considered as having been impressed during Jurassic times.

In general, it may be said, the expression of the younger system of tectonics is mainly that of faulting; that of the more ancient that of flexing. That the two are widely separated in point of time is a fact which usually does not appear to have been clearly distinguished in any part of the desert region, and especially in the Great Basin province, where the tectonics of the arid country has been chiefly studied. In this last named province it is the older system of tectonics that is most conspicuous in the bare mountains and that is most clearly open to observation.

Nature of the Younger Tectonics

As already noted, the most characteristic feature of the younger system of tectonics is the fault. Usually it is assumed that there is only a single line of dislocation blocking out each mountain ridge. In reality, the total amount of displacement is attained by compound or repeated faulting. The accompanying effects are imposed on all other older geologic structures. Their immediate influence is to disguise more or less completely the older tectonics.

When of very late occurrence faulting may make itself conspicuous in the landscape; in all other cases the topographic effects are quite generally obscured by erosion. Complete mastery of the acquired geologic structures by erosion appears to be especially true of the Great Basin region.

In the light of the newest observations it is somewhat difficult at the present time to say with confidence just how far recent folding has impressed itself upon the strata of the Great Basin province. So far as my own investigations indicate, the effects appear to be very slight and local. In those localities in which flexing has been regarded as best displayed careful inquiry has in every case failed to substantiate the claims. It is concluded that most of the Appalachian structures ascribed to the ranges of this region will be found to belong mainly to the older period of mountain building instead of to the younger period.

There are several localities in Nevada in which gentle folding is regarded by some observers as having taken place during Late Tertiary or

Early Quaternary time. With the old Paleozoic beds are involved well stratified clays and sands, 4,000 feet in thickness, presumably of Eocene or Miocene age. A critical cross-section of the strata is one given by Spurr of the Furnace Canyon, between the south end of the Grapevine Mountains and the northern extremity of the Funeral range. For a distance of more than 150 miles these two ranges form the eastern wall of the deep Death Valley. The apparent low arch of Tertiary strata may be due to near-by faulting of profound character rather than to the action of compressive forces. The axis is parallel to the great fault-lines bordering the Grapevine Mountains, and it is also near the principal displacement plane in the Funeral range. The altitude of the inclined Tertiary beds at the south end of the last mentioned ridge is also more readily accounted for by faulting than by normal flexing.

A hundred miles to the south of the last mentioned locality are Tertiary beds the altitude of which is nearly vertical. This disposition of the strata may be also due to faulting and not to folding. There are other localities displaying the same phenomena, but in no instance at present recalled can marked normal flexing be unqualifiedly ascribed.

Character of the Older Tectonics

General Features

With the older tectonic features flexing is dominant. Reversed as well as normal faulting is of frequent occurrence. The geologic period during which the most pronounced structures were acquired is believed to be the Jurassic. All previously formed structures were then largely disguised or obliterated.

In arid America, outside of the Great Basin province, little reference has been made to the older tectonics. Allusions to them in this area have been not only few, but they have been incidental and general rather than specific in character. King,[4] in 1878, notes the mere existence in some of the Nevada ranges of geologic structures formed before the present mountains were reared above the plains. Russell[5] also makes passing mention of similar phenomena in the same region. Considering the main groups of ranges as probably outlined in pre-Tertiary times, when the region was finally uplifted above the sea, Spurr[6] explains the present features by assuming the early dissection of the country when there was supposed to be greater precipitation than at present and when there

[4] U. S. Geological Exploration of the 40th Parallel, vol. i, 1878, p. 715.
[5] U. S. Geological Survey, Monograph XI, 1885, p. 26.
[6] Bulletin of the Geological Society of America, vol. 12, 1901, p. 266.

existed many actually flowing rivers. Special stress is also placed on warping, folding, and faulting that "went on continuously all through the Tertiary into the Pleistocene, and is even now progressing."

Toward the northern end of the Mexican tableland, in New Mexico, the ancient tectonics is well displayed. Some of the details I have recently described[7] at some length, although it is not as yet at all certain that all of the thrust-planes recognized can be regarded as belonging to the earlier period of deformation. On the whole, the general character of the ancient tectonics is that of gentle plication in contradistinction to that of the more recent structures which are principally due to faulting.

OLDER GEOLOGIC STRUCTURES OF THE GREAT BASIN REGION

Of the four grand provinces of the arid region the Great Basin is physiographically the oldest. Only locally is the topography at all youthful. Over most of the area the mountains are worn down to comparatively inconspicuous eminences, so low that with some exceptions forests no longer cover their summits. They are described as buried up to their shoulders by detritus. Irrespective of structure, they everywhere appear to be made up of the most resistant rocks.

The rocks are mainly hardened limestones, indurated sandstones, and eruptives. The contrasts of distinct and regular hard and soft rock-belts, such as are found elsewhere, are not so strong as in some of the other parts of the arid region. Viewed in the light of a distinct geographic cycle for an arid climate we have to look to mountain-making agencies other than deformation and dislocation for an adequate and satisfactory explanation of the present configuration of the individual Basin ranges.

Although mountain ranges of the Great Basin province display both gentle folding and profound faulting, the main effects of these have been manifestly long since mastered by vigorous desert-leveling, as Spurr has well urged. The most pronounced flexing and most of the faulting is relatively old—pre-Tertiary at least. Nowhere does there appear to be any genetic relationship between the rearing of the mountains and these foldings. The present mountains, therefore, seem to owe their existence not so much to general flexing or to recent and profound faulting as they do to the differential effects of true desert-leveling, in which the most resistant rocks longest retain the highest elevations.

Critical inspection of the various diagrams of the Basin ranges, as

[7] Journal of Geology, vol. xiii, 1905, pp. 63-70.

given by King,[8] Gilbert,[9] Spurr,[10] and others, at once discloses the fact that there is a general independence of mountain profile and geologic structure. This feature is still more impressive in the field. Concerning this point, Lauterback's discussion of the Humboldt Mountains and their structure has a special bearing.[11]

TYPES OF ANCIENT STRUCTURES OF THE BASIN RANGES

Some of the more frequently occurring types of geologic structures which the Basin ranges present may be especially noted for the reason that, notwithstanding the great variety displayed, there appears to be so little direct or genetic relationship existing between the tectonics and the configuration of the mountains. It is to be noted that the several flexed types are all of the most open character. It is a significant fact that in nearly all of the original representations of the geologic cross-sections the actual presence of faults is so rarely recognized. This doubtless arises from several obvious and distinct causes. It is for such reasons

FIGURE 1.—*Cross-section of the Humboldt Range*

as these that Dana,[12] after exhaustively reviewing the literature of the subject in all its various phases, was led to the conclusion that the fault hypothesis of Basin Range structures was insufficiently supported by the data published.

Field investigations recently carried on seem to demonstrate that in the cases of many of the ranges in which faults have been wholly unrepresented in the diagrams dislocations are not only actually present, but some of them are of great throw. These faults are not necessarily normal ones. It now seems quite possible that some of them at least may be thrusts, which also originally reared mountains. The entire provincial geologic column being made up of hard and brittle rocks, the zones of shearing would be very thin and the angles of the planes with the horizontal very high.

[8] U. S. Geological Survey of the 40th Parallel, vol. i, p. 451 et seq.
[9] U. S. Geological and Geographical Survey West of the 100th Meridian, vol. iii, p. 27.
[10] Bulletin of the Geological Society of America, vol. 12, pls. 24 and 25.
[11] Bulletin of the Geological Society of America, vol. 15, 1904, pp. 289-346.
[12] Manual of Geology, fourth edition.

An uncommon type of ancient tectonics is displayed in the Humboldt range. The general attitude of the strata is that of a low and simple arch, the crest of which has been planed off, disclosing a central core of Azoic crystallines. Modified from King, the structure is as represented in figure 1.

A more complex form of flexing is shown in the White Pine range. The general surface of the district, which is evenly beveled, gives no suggestion of an anticlinorium. There is, however, much detailed work

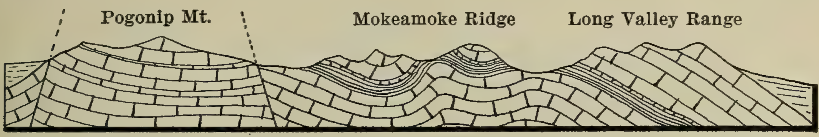

FIGURE 2.—*Geologic Cross-section of the White Pine Range*

needed in this range before the real significance of its structure can be made out. It is probable that in Spurr's diagram (figure 2) certain fault-lines are omitted.

In the Funeral range there is the unusual phenomenon of soft Tertiary beds constituting the main part of the mountains. These soft strata are over 4,000 feet in thickness. They have been described as furnishing critical evidence of very recent folding in all of the mountain ranges of

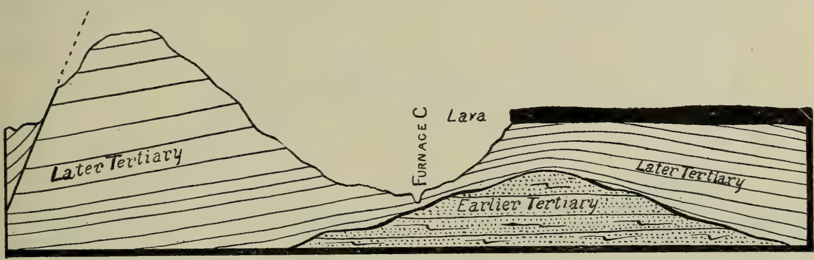

FIGURE 3.—*Apparent Folding of Tertiary Beds of the Funeral Range*

the Great Basin province. There appear to be in the Tertiary sequence of strata an older section and a younger section, separated by a well marked unconformity, which seems to indicate a true erosion interval. The apparent fold in the beds is certainly due to the later layers resting on the inclined surfaces of a ridge of the earlier sediments which are now relatively hard sandstones. Opposite Mount Blanca the axis of the apparent anticline is in the middle of the Furnace Creek valley, but 10 miles to the south of this point the axis passes 2 miles to the east of the creek under the basalt field (figure 3).

The inclination of the Tertiary beds is further emphasized by near-by faulting. It seems very doubtful whether normal flexing has taken place to any appreciable extent.

At the south end of the Grapevine Mountains, and about 8 miles east of the last mentioned locality, is a similar phase involving Tertiary strata.

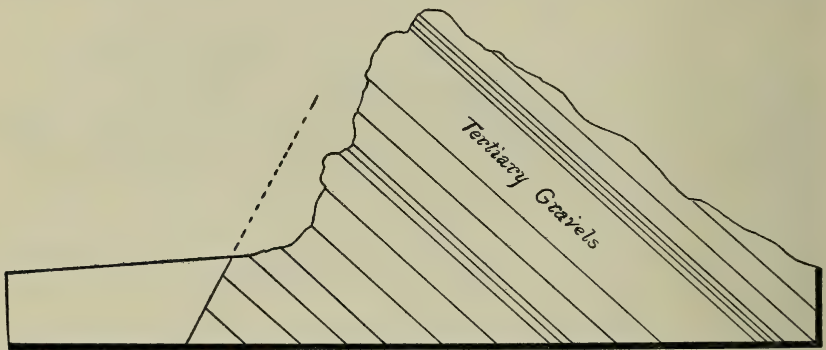

FIGURE 4.—*Tilted Tertiaries of the Grapevine Range*

The rocks are highly tilted and rise 2,000 to 3,000 feet above the plains. They are composed largely of coarse materials, gravels and sands, more or less firmly cemented. Their high inclination appears to be due entirely to faulting. This mass of rock forms an integral part of the tilted block constituting the main range (figure 4). The structure is that which is commonly called simple monoclinal.

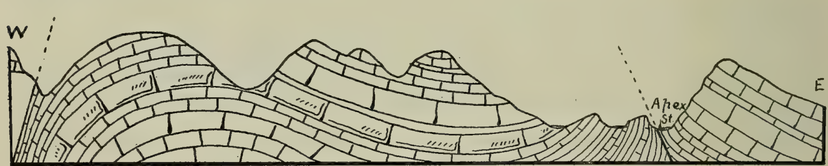

FIGURE 5.—*Ancient Structures of the Vegas Range*

Like phenomena, also involving hard Tertiary gravel deposits of great thickness, are seen 60 miles to the southward at the south end of the Funeral range.

The Vegas group of mountains is rather complicated. While there is some gentle flexing, the principal tilting of the strata appears clearly to be the result of deformation accompanying faulting. It is not improbable but that several of the most conspicuous ranges have been formed directly through thrust-action. At any rate, the present configuration of the mountains gives no suggestion of the slightest genetic relationship between profile and structure. The contours of the ranges are those of general differential erosion under ordinary conditions of an arid climate (figure 5).

A simple synclinal structure is represented in the Spring Mountains, at the extreme southern point of Nevada (figure 6). Here again the earlier observations are at fault in not disclosing important dislocations.

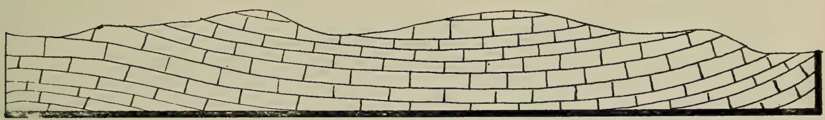

FIGURE 6.—*Ancient Syncline of the Spring Mountain Range*

It is now known that there are in this range numerous and profound faults. Existence of some of the more pronounced faults should have been at least suspected long ago, as they are clearly visible from the town of Las Vegas, a distance of 15 miles. It is quite manifest that the profiles of the range do not bear any relation whatever to the geologic structure.

Not very unlike the Spring Mountains in structural character is the Grant range in central Nevada. There is here represented in the cross-

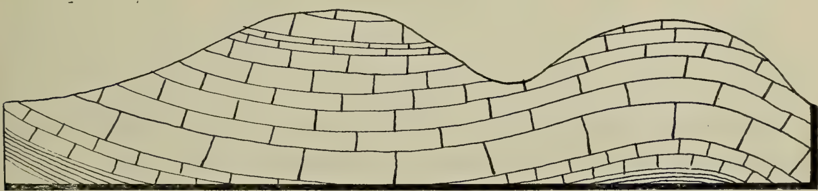

FIGURE 7.—*Old Arch and Trough of Grant Range*

section both an arch and a trough (figure 7). Were the eastern ridge of the range alone considered, there might be some ground for regarding as possible a close relationship between the mountain contour and its structure; but in the ridge on the west side the strata of the high parts are disposed in a syncline. There are reasons for believing that profound faulting exists near the eastern foot of the range. The configuration of the mountain is easy of explanation on the hypothesis of general desert-leveling, but extremely difficult on any other theory.

The cross-section of the Hot Creek range (figure 8), as given by Spurr, presents almost conclusive evidence of the perfect independence of the rearing of the mountains and the flexing of the region. In a broad way a part of the range may be regarded as a low arch repeatedly faulted and covered on one side by an immense thickness of eruptives. The profile is mainly erosional, not structural.

That there was some orogenic movement of the region of the nature of faulting rather than flexing is shown in the dislocations which the

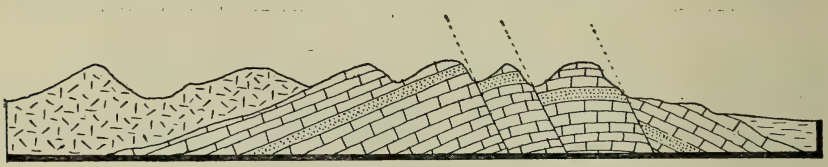

FIGURE 8.—*Faulted Arch in Hot Creek Range*

very late basalt flows have undergone. This phase of the subject has also been taken up by Lauterback[13] in western Nevada. This author's Muttleberry Canyon cross-section (figure 9) of the Humboldt range is well worth careful examination in this connection.

Numerous examples other than those mentioned above are given by Spurr.[14]

So far as the Great Basin province is concerned the accumulated testimony goes to show that the characteristic flexure structures of the moun-

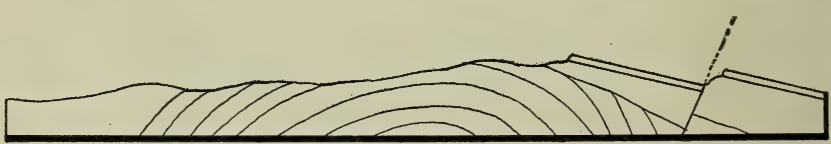

FIGURE 9.—*Ancient and Recent Tectonics of Humboldt Range*

tain ranges that are displayed at the present time are mainly those of an ancient system of tectonics, in no way genetically related to the rearing of the mountains as they now appear, as noted by Dutton and Russell especially; that in some of the ranges the rock-complex, with its ancient tectonic features, has been faulted in comparatively recent times, and that these minor slippings have more or less clearly impressed themselves upon the local relief by producing tilted block-ridges, as lately described by Spurr, Lauterback, and Davis; that in the majority of cases the great

[13] Bulletin of the Geological Society of America, vol. 15, 1904, pp. 289-364.

[14] Bulletin of the Geological Society of America, vol. 12, 1901, p. 217.

faults which might account for the average Basin range are old events, as considered by Dutton and Spurr; that most of the present mountains rise above the general plains-level largely for the reason that they are erosional residuals, composed of the more resistant rock-masses in the midst of weak rock areas, as early urged by King and later by Spurr; that the general shapes of the individual residuals are controlled to a very appreciable extent by the ancient geologic structures, frequently accentuated, perhaps, by late minor fault-movements; that it is possible to formulate the salient Basin-range features by the aid of direct eolic denudation of an anciently faulted and folded region, in accordance with the present known workings of general desert-leveling under conditions of aridity, as I have more fully set forth in another place, and that the present tilted aspect of so many of the desert ranges is largely illusory, because in anciently broken and inclined strata which had been planed off the soft beds have been profoundly stripped from the resistant layers, leaving the residual ridges with long, bare backslopes, as particularly noted in connection with the descriptions of the so-called tilted block-mountains of the Mexican Tableland province.

OLDER GEOLOGIC STRUCTURES OF THE COLORADO PLATEAU PROVINCE

With a few minor exceptions, the mountainous elevations which rise above the general plains-surface of this area are chiefly of volcanic origin. It is a remarkable fact that almost the entire surface of this vast area is essentially a stratum plane, or at least the hard layers are arranged *en echelon.* Unlike in any other part of the country surrounding, there is, on the whole, little evidence of marked folding of the Appalachian type. In the main, the whole province is a simple, single, quaquaversal arch. Typical Basin-range structure is, therefore, practically wanting.

Only around the margins of the great dome is there noteworthy faulting. It was on the Great Basin side of the dome that Gilbert gained his first conceptions of the faulted and tilted blocks that afterwards were made to stand for his idea of the Basin-range type of mountain structure. With the great simplicity of structure so apparent, there was seemingly at that time no other alternative but to extend the profound faulting of the Grand Canyon region indefinitely over the plains beyond.

OLDER GEOLOGIC STRUCTURES OF THE CALIFORNIAN GULF BASIN

In the valley of the lower Colorado River and the adjacent country on both sides, in southern California and southern Arizona, the mountains are composed largely of great successions of pyroclastic beds interspersed with thick lava-flows. The lavas are presumably early Tertiary in age. Through frequent and extensive faulting, old continuous fields of erupted rocks are now disposed as broken and apparently tilted blocks, as in the case of the sedimentaries in other parts of the arid region. Little of the Paleozoic and Mesozoic strata is now displayed anywhere within the province. Where the old formations have been observed, as in the Prescott Forest Reserve, the Paleozoics show marked deformation.

Although the mountain ranges of this province rise higher and more sharply above the plains-surface than they do anywhere else in the desert region, so very little of the older tectonics is open to inspection that from the visible ancient structures alone it would be difficult to say just how much flexing has had to do with mountain rearing. It is, however, manifest that whatever flexing is observable, it is quite ancient, and that there is little or no effect apparent from recent folding. The 3,000 to 5,000 feet of section which the mountains expose above the plains are largely made up of the thick lava-flows and the interbedded tuffs. The only geologic structures which can have any close relationship with the rearing of the mountains is profound faulting.

All evidences in this province seem to point conclusively to the fact that the mountains for the most part at least are true residuals, fashioned perhaps from faulted blocks, under conditions of general desert-leveling. McGee's[15] observations in the Sonoran district of northern Mexico also furnish incontestable testimony in support of this suggestion.

OLDER GEOLOGIC STRUCTURES OF THE MEXICAN TABLELAND

Several factors contribute to make the Mexican tableland a region especially instructive in the present connection. In comparison with the other three provinces mentioned there has been less volcanic action. The topography is much newer. The mountains appear to be more strictly of the ideal Basin-range type. There are clear and abundant evidences of ancient and profound faulting by which the mountains were originally blocked out. There are positive proofs that late folding has not contributed to any appreciable extent to the rearing of the ranges. The flexing and most other features accompanying great compressive action are clearly shown to have been already in existence in mid-Cretacic times. The ancient tectonics are sharply set off from those more recent and are of a very different character.

Near the north end of the province the Sandia and Manzano ranges display typical features (figure 10). The throw of the main fault is at

[15] Bulletin of the Geological Society of America, vol. 8, 1897, pp. 87-112.

least 4,000 feet. The general geologic section across the northern end of this province, about at Engle, may be indicated as in the following dia-

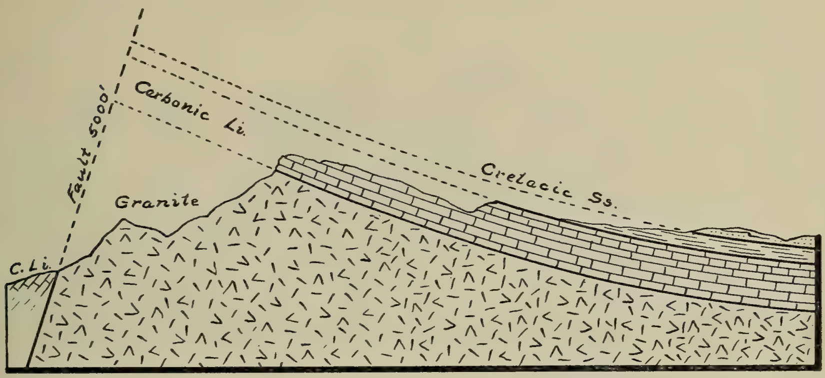

FIGURE 10.—*Geologic Cross-section of the Sandia Range*

gram (figure 11). The distance is about 60 miles and the height of the summits 8,000 to 10,000 feet above tide-level.

FIGURE 11.—*Structure of the north End of Mexican Tableland*

The ancient tectonics of some of the ranges of this province are best indicated in diagram. Near Palomas Gap, in the Sierra de los Caballos, a thrust-plane is finely displayed. A cross-section of the range near the point mentioned is represented as follows (figure 12):

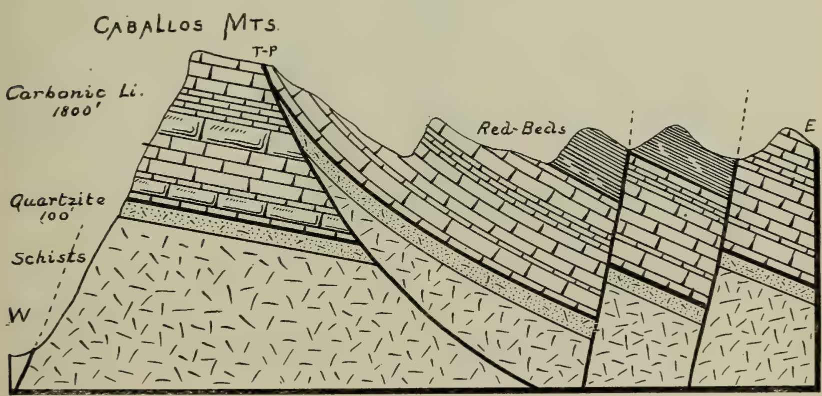

FIGURE 12.—*Old and Young Tectonics of Caballos Range*

Near the north end of the same range, Caballos Peak, which rises 4,000 feet above the plains, shows the following structure (figure 13):

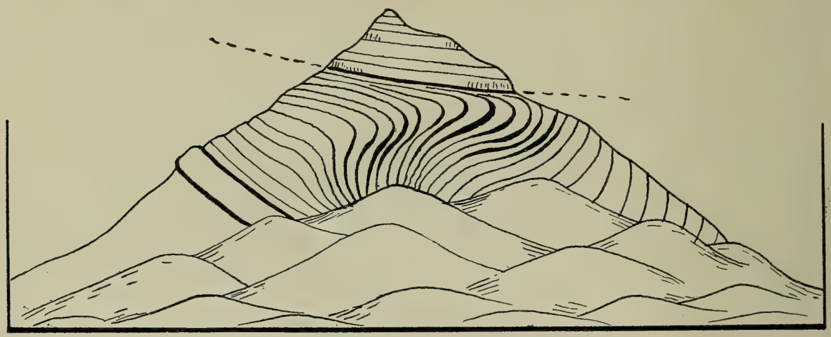

FIGURE 13.—*Thrust Plane in Caballos Peak*

On the Chupadera Mesa, in the eastern part of Socorro County, New Mexico, the Carbonic limestones, for a distance of 1,000 feet on either side of a huge dike, are upturned and the whole planed off and covered by horizontal Cretacic sandstones (figure 14).

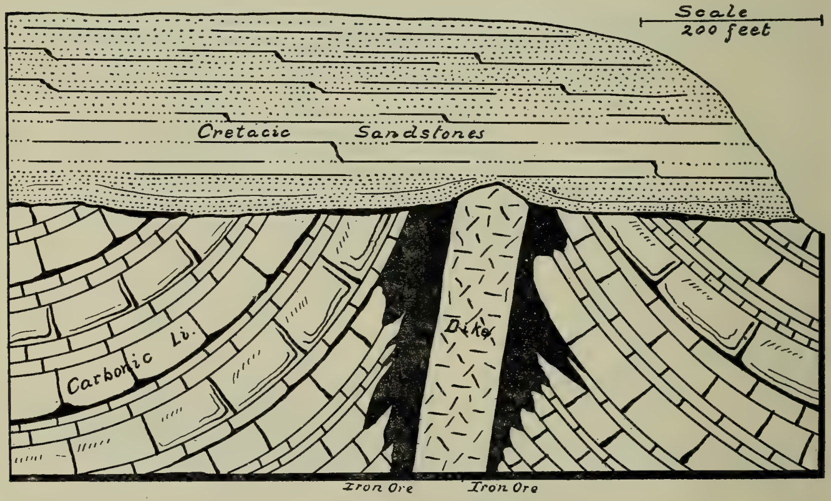

FIGURE 14.—*Ancient Tectonics of Chupadera Mesa, New Mexico*

Illustrations of these phenomena might be repeated indefinitely. It suffices to say that they all go to show in a conclusive manner that the more conspicuously folded structures usually observed in the Desert ranges belong to an ancient system of tectonics and have no genetic relations with the rearing of the mountain ranges themselves.

Relations of the Mountain Ranges to Flexures

From the records of the observations recently carried on in all four of the grand divisions of the American desert region the accumulated evidences seem to be conclusive that the main flexing of the strata is very much older than the present mountains possibly can be. The ancient tectonics does not appear to be obliterated, or even notably disguised, by any of the post-Triassic movements. As indicated by all the known geologic cross-sections of the mountain ranges, the form of the latter can not be regarded as having any direct genetic relationship whatever to the flexed structures of the rock-masses. Arches, troughs, monoclines, and flat-lying masses are truncated alike. Mainly to differential erosion must the present surface inequalities be considered as owing their origin, and the erosion is regarded as deflative in character.

Geologic Evolution of Desert Ranges

The anomalous climatic conditions of the desert region and the general activities of desert-leveling or deflation have been already discussed in another place.[16] No specific application of the principles to the moulding of the Basin ranges, or rather Desert ranges, has yet been made. The idea of desert-leveling, as now understood and applied to the Basin ranges, does away with many of the obstacles which the fault theory has long encountered. It does not necessitate the postulation of a former humid climate and the development of wide branching drainage systems, as recently urged by Spurr.[17] It makes it possible to formulate a connected system of the salient geographic features of the region through mere means of general wind denudation. The general relief effects are not very unlike what they are in more humid lands, as the Appalachians, differing chiefly only in the character of the principal erosive agency.

According to the principles of general desert-leveling by deflation it is not necessary to fancy, for the beginning of an arid cycle, an even surface like a peneplain. Whatever the nature of the relief when such a cycle began, the most active erosive forces would commence work just as they found it. They would soon fashion all features after their own way.

[16] Bulletin of the Geological Society of America, vol. 19, 1908, p. 63.
[17] Bulletin of the Geological Society of America, vol. 12, 1901, p. 266.

The soft rocks would be acted upon much faster than the hard ones, just as in a humid country. The tendency would be naturally to greatly accentuate the larger geologic structures. The latter would be expressed in the topographic forms as clearly as they are in such districts as the Appalachians or the Juras. Desert erosion has gone on so long and so extensively in the region under consideration that all the landscape shapes now may be regarded as the direct products of deflative erosion, except in a comparatively few instances where there is some modification on account of recent minor faulting.

First reviewing deductively the field of Basin-range genesis, as displayed in the northern part of the Mexican tableland, it seems wholly inadequate, with existing conditions of an arid climate imposed, to postulate a development of the present mountains by direct rearing through profound fault movements.

FIGURE 15.—*Apparent Basin-range Structure in the Mexican Tableland*

Assuming the initial factor of an upraised peneplain in a region which had been previously gently flexed and profoundly faulted, such as the New Mexican area appears to have been, with great thicknesses of weak strata 10,000 to 15,000 feet in vertical measurement, overlying an equally thick section of beds of very resistant character, the most noteworthy feature in the areal distribution of the geological formations would be the marked alternation of belts of hard and soft rocks. The ideal general tectonics of the region is, therefore, that of the typical Basin-range structure. This is represented below (figure 15) of an actual section across the Jornada del Muerto, in southern New Mexico,[18] in which the dark band is the great Carbonic limestone formation.

When, however, we come to look for evidences of actual fault-lines we do not find them where we would expect them to occur, on the theory that the mountains were reared by fault-movements of 4,000 to 10,000 feet—that is, at the bases of the so-called range-blocks, where mountain sharply meets plain—but when they occur it is invariably far out on the

[18]Journal of Geology, vol. xiii, 1905, p. 67.

latter. It is, in fact, about as far from the fault-line to the crest of the range as it is from the latter to the base of the backslope. As a rule, the ranges are bilaterally symmetrical. They would hardly be so if they were recently reared and tilted fault-blocks.

For simplicity, four distinct stages of Desert-range development may be premised. First is the period of completed sedimentation, represented by the general geologic column. Of this we have ample evidence in the sequence of geologic formations represented in the different parts of the region. Above the great thickness of hard Paleozoic limestones come non-resistant beds consisting of 3,000 feet of red-beds (1,000 feet of which are Mid-Carbonic in age, 1,000 feet of Late Carbonic, and 1,000 feet of Triassic age), a varying thickness of soft Jurassic sandstones, 7,000 feet of Cretacic shales and sandstones, and, finally, 5,000 feet of Tertiary beds.

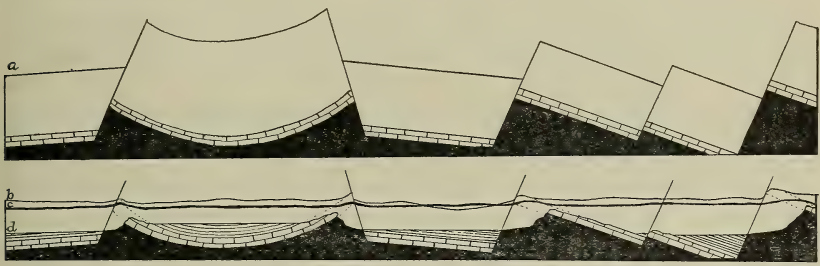

FIGURE 16.—*Stages of Development of Desert Ranges*

In point of time, according to our best information, the major flexing of the region took place in Jurassic times, the major faulting in early Tertiary times. Unaffected by erosion, the dislocations would give results similar to those shown in the diagram below (figure 16, *a*). Deformation and erosion no doubt went on simultaneously, giving a more or less subdued profile, represented by the line *b* in figure 16. As erosion progressed the country must have been reduced practically to the condition of a peneplain (line *c*, figure 16), with possibly here and there some of the older and harder rock-masses protruding above its even surface. The remnants of this great plain beveling the substructure everywhere appears to exist in that high-lying mass constituting the Raton range in northeastern New Mexico, the flat summit of which is known as the Mesa de Maya.[19] Indications of general peneplanation are also shown in many of the other plateau plains of the region.

[19] Proceedings of the Iowa Academy of Sciences, vol. xiii, 1908, p. 221.

The fourth stage may be considered as beginning with the peneplain upraised high above the sealevel, the introduction of arid climatic conditions, and the full play of eolic erosional influences producing after a long time the present day facial expression of the country (line *d*, figure 16).

With these purely deductive conclusions the facts observed seem strictly to accord. A concrete, and at the same time most typical, example is the great San Andreas ridge in southern New Mexico, directly north of El Paso. Its crest is 4,000 to 5,000 feet above the plains and 9,000 to 10,000 feet above sealevel. Of all the desert ranges, this one would seem to present most clearly a tilted fault-block rising abruptly out of a vast sea of earth. For a distance of 100 miles the steep eastern face of the range appears to be as true a faultscarp as is to be found in any ideal Basin range.

When the critical evidences are sought of recent upraising and tilting of this long mountain block, and, indeed, of other similar ranges, they appear to be lacking in a surprising manner. The fault-line is found to be located several miles out on the plains, far beyond the base of the mountain. A transverse profile of the range shows it to be rather symmetrically developed, with the crest-line nearly midway between the fault-line and the base of the backslope. The plains on either side have rock-floors. The long, narrow belt of remnantal mountain rock is bordered by broad areas of weak shales. Very inadequate explanations at once appear in the fault hypothesis of the rearing of the mountain range. One must turn to some other suggestion for the great mountain-forming agency. Nor does ordinary erosion suffice. In view of the well known deficiencies of rainfall, with the still more marked absence of running waters, one is tempted to seek some erosive process other than stream action. It is in the arid region that the eolian influences find their maximum activities as erosional processes.

Under conditions of aridity, the differential effects of wind-scour, or deflation, upon rock belts of contrasted induration are very different from what they are in a normal humid climate. The inequalities of surface relief are in consequence very much more rapidly accomplished than when stream-action is the chief eroding process. In general, it may be stated that in the case of hard rock-masses in an arid land eolic erosion is probably less than one-tenth as efficient as in a normal humid country water action would be, while in the case of weak rocks it is more than 10 times greater. This is, no doubt, the principal reason why to most observers in the desert regions such manifest evidences of enormous erosion are so impressive on every hand, while the recognized absence of an abundance of running waters makes it appear that the progress of erosion must be extremely slow. The latter is, of course, the only possible alternative when water is assumed to be the sole erosive agent.

Recapitulation

From the foregoing consideration of the most obvious geologic structures presented by the Desert ranges of western United States, it appears that:

1. The folded structures, such as are displayed in some of the Basin ranges and by many of the Desert ranges outside of the confines of the Great Basin, belong chiefly to an ancient system of tectonics (Early Mesozoic).

2. These flexed structures have usually no direct genetic relationships with the rearing of the present mountains.

3. The major faulting is also mainly old and long since completely mastered by erosion, and has small direct connection with the rearing of the present ranges.

4. The entire flexed and faulted region was planed off to the condition of a peneplain before it was upraised and presented to the sculpturing agencies through which the present mountains took form.

5. The tectonics of the region have merely an accidental rôle rather than a direct genetic influence in the shaping of the Desert ranges. The present facial expression of the arid region and its evolution into abrupt, narrow, and lofty mountain ranges and broad, even plains are due directly to the differential effects of general desert erosion on alternating belts of very resistant and very weak rock-masses.

6. The present profiles of the desert ranges are thus largely independent of faulting movements, and the erosional shapes assumed only emphasize the gently flexed bedding structures.

7. The general desert-leveling and lowering of the country goes on much in the same way as planation proceeds in humid regions, except that there is no downward limitation at sealevel.

8. The differential sculpturing of erosion under conditions of aridity are very different from those in a humid climate, in that the deflative effects on the more resistant rock areas are very much less vigorous than those of normal corrasion, and on the weak rock belts very much more powerful.

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DEFLATION AND THE RELATIVE EFFICIENCIES OF EROSIONAL PROCESSES UNDER CONDITIONS OF ARIDITY[1]

BY CHARLES R. KEYES

(Presented by title before the Society December 29, 1908)

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INTRODUCTORY

The desert has given us the two great laws on which rests the entire scheme of ancient and modern landscape evolution. Arid regions have supplied the fundamental data for a general plan of land sculpturing that is in its nature strictly genetic. It is, indeed, as recently stated, a notable fact that the waterless waste should furnish us first glimpses of

[1] Manuscript received by the Secretary of the Society August 16, 1909.

the mutation of land forms in the humid countries. One of the great principles thus formulated has been so suggestive of tangible results in the land of its birth that it has done more, perhaps, than any one factor to cast into shadow the other. The geologic processes whereby the second basic principle manifests itself have been until very lately almost wholly overlooked.

FIGURE 1.—*Geographic Provinces of Arid United States and Northern Mexico*

It is the arid region which has introduced to us an erosive agent more potent than corrasion, more constant that the working of the rains, more extensive and persistent than the encroachment of the sea. Eolian erosion, wind scour, or eolation, must ever grow in effectiveness as the history of our globe goes on and erosion lasts. It may be that in the lineaments of our moon we see the final effects of eolic powers.

Powell's deductions[2] regarding denudation in the dry regions of western United States led to the great generalization of the baselevel of erosion. Not less important and far reaching was the later deduction of Passarge[3] of desert-leveling without baseleveling. For the development of these basic ideas into a general, definite, and systematic working scheme chief credit, of course, belongs to Prof. W. M. Davis. This author has developed the normal cycle of land degradation;[4] he has presented a plan of a cycle of erosion under glacial conditions,[5] and more recently he has discussed a geographic cycle in an arid climate.[6]

It is to the operation of certain processes of general denudation under conditions of aridity that attention is here called. Two features in particular, the relative efficiencies of the different erosive agencies in a dry climate and the probable character of the general surface relief of the American desert region at the beginning of the present arid period, have not as yet been accorded the critical consideration that they seem to demand. For obvious reasons specific illustration is drawn here mainly from the desert regions of southwestern United States and from northern Mexico. In a general treatment of the subject later on, facts from other desert districts of the globe will be more fully considered.

The published descriptions of American arid features relate principally to the Great Basin. The desert region of this country is, however, a far greater expanse. Of it the Great Basin is only a minor part. Its major distinctive provinces are known as the Great Basin, the Colorado plateau, the Californian Gulf basin, and the Mexican tableland. For purposes of present discussion the approximate boundaries of these provinces are indicated on the accompanying sketch map (figure 1) of western United States.

General Characteristics of the arid Country

Among the most distinctive peculiarities of the desert region, and those which present the strongest contrasts to the relief expression of moist countries, may be mentioned the following characteristics:

1. Vastness and evenness of the intermont plains;[7]
2. Complete encirclement of the mountains by plains;[8]
3. General isolation of the mountain ranges;
4. Characteristic absence of foothills around mountain ranges;
5. Great resistance to erosion of the mountain rocks;

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[2] Exploration of the Colorado River of the West, 1875, p. 207.
[3] Zeitsch. d. deut. geol. Gesellschaft, LVI Bd., Protokol, 1904, p. 193.
[4] National Geographic Magazine, vol. i, 1888, pp. 11-26.
[5] Proceedings of the Boston Society of Natural History, vol. xxix, 1900, pp. 273-322.
[6] Journal of Geology, vol. xiii, 1905, pp. 381-407.
[7] Keyes: Bulletin of the Geological Society of America, vol. 19, 1908, p. 63,
[8] Journal of Geology, vol. xvi, 1908, p. 434.

6. Soft substructure of the plains which constitute four-fifths of the entire desert area;[9]

7. Remarkable beveled rock structure of the plains surface;[10]

8. Plains character of the intermont rock-floors themselves;[11]

9. Representation of former plains-levels by the plateau-plains;[12]

10. Remarkable thinness of the surface mantle of many plains;

11. Transported nature of the surface materials;

12. Marked tendency of the surface mantle to make the plains smoother;

13. Gravelly character of the surface mantle only apparent;

14. Notable absence of normal rock-weathering;

15. Absence of distinct waterways on the plains;[13]

16. Extent of sheetflood transportation.[14]

There are other major features which need not be enumerated in the present connection, and many minor characteristics of which even a list would be of great interest. Some of these desert features have not been especially noted. The origin of many of them has been ascribed to the same erosive processes which are most active in the more familiar humid regions. Only recently have the older interpretations of desert structures been questioned. The later writings of Walther, Spurr, McGee, Passarge, Davis, Penck, Keyes, and Cross contain many statements suggesting that the new explanations must now be sought if we are to satisfactorily account for many of the physiographic aspects of the desert regions. That the features mentioned are distinctive of arid countries and find no counterpart in the humid lands is only beginning to be generally appreciated. Eolative phenomena are as varied and as peculiar to the desert as are the ordinary erosional effects by running waters under normally wet climatic conditions.

The critical criteria for recognizing eolative effects are discussed at length in another place. Typical views of some of the most characteristic relief features I have presented in a recent bulletin of the Geological Society of America,[15] to which reference may be made.

Peculiarities of an Arid Climate

In the present connection only the more striking features of an arid climate need be mentioned as bearing directly upon the phenomenon of

[9] Bulletin of the Geological Society of America, vol. 19, 1908, p. 76.
[10] American Journal of Science (4), vol. xv, 1903, p. 207.
[11] Engineering and Mining Journal, vol. lxviii, 1904, p. 670.
[12] Proceedings of the Iowa Academy of Sciences, vol. xiii, 1908, p. 221.
[13] American Geologist, vol. xxxiv, 1904, p. 160.
[14] American Journal of Science (4), xxiv, 1907, p. 467.
[15] Bulletin of the Geological Society of America, vol. 19, 1908, p. 570.

eolation. Most influential is, of course, deficient rainfall—under 10 inches annually—none or very little of which ever reaches the sea. On the plains, which occupy four-fifths of the entire arid area of the United States, the yearly precipitation is often no more than one-half of this amount, while on the higher mountains it is several times as much. Evaporation is high, frequently ten times as much as the precipitation. Vegetation is sparse and does not bind the soil. Rock wasting is mainly mechanical rather than chemical.

The small rainfall gives little opportunity for appreciable stream work. Only in the loftier, forest capped mountains does water action at all approach normal; but these spots are very insignificant in extent compared with the size of the whole desert. The mountain streams are, as a rule, shorter than their slopes. There are only few traces of waterways on the plains. Few or no perennial streams originate within the arid limits. The few rivers which are found in the desert region merely traverse it on their way to the ocean, their headwaters being extralimital. Whatever running water there is comes from the infrequent and local "cloudbursts," and these sporadic flood-waters spread out over the smooth plains in broad sheets rather than in the usual restricted streams.

The dry, pulverulent soils and the bare rock outcrops, unprotected by plant growth, give unusual opportunities for vigorous eolian erosion and extensive transportation of the finer rock-waste by the winds, for the latter are constant and strong. In the absence of sufficient rainfall, eolative processes are at their best, and as geologic agencies of erosion attain an importance that is wholly unknown in humid lands.

Rock-weathering in Desert Regions

Before considering the relative efficiencies of the several degradational agencies in the desert region, there should be briefly contrasted some of the differences in character of the materials worked on in a normal humid climate and under conditions of aridity. Restricting the term rock-weathering to those superficial changes which rock-masses undergo when exposed to the air, and which finally encompass their complete destruction as distinct geologic units, such compositional modifications of the rocks in a dry climate present many peculiarities.

While it is generally recognized that the continual breaking down of geologic formations at the surface of the ground is both chemical and mechanical in character, it is well known that a clear distinction between the two processes is not always made. In the moist climates, where most of us have had our widest geologic experiences, chemical decomposition of the rocks so very greatly predominates over their mechanical disintegration that often the latter in comparison is scarcely noticeable. In the arid regions not only is the very reverse true, but it is so to a preeminent degree.

It is a well known fact that the chemical decay of rock-masses takes place with greatest facility under conditions of heavy rainfall and warm climate. Rock decay appears to be, as Russell[16] has observed, the direct result of normally wet climatic conditions. In cold or arid regions the rocks are scarcely at all decayed.

On the moist Atlantic slope, within the granite areas of the Piedmont plateau of Maryland, for example, complete rock decay has been noted[17] to extend to depths of 40 to 50 feet. Farther south, in the Coosa Valley of Alabama, general decomposition of the rocks frequently reaches depths of 200 to 300 feet. Derby[18] has shown that in Brazil chemical breaking down of the rocks attains even greater depths than any of those mentioned. Under especially favorable structural conditions, as in the case of fault-planes, mineral veins, and other local influences of like nature, rock decay sometimes goes on to distances of more than 1,000 feet from the surface of the ground. Almost everywhere in a moist climate rock decay takes place faster than the decomposed materials are removed.

In marked contrast to the breaking down of rock-masses in the moist regions, the arid lands present extensive bedrock surfaces showing little or no signs of real decay. Destruction of these rocks is almost entirely mechanical in character; in comparison the chemical effects are practically *nil.* The slightest amount of chemical decomposition which rock materials undergo at the ground surface is well shown by the great talus slopes and other accumulations of colluvial deposits that form veritable rubble piles of ponderous size, and with materials so fresh to all appearances that they seem to have come direct from some gigantic rock crusher. Even the adobe soils of the arid region, when examined under the microscope, attest the strictly mechanical origin of the finer materials.

In the desert region of the West, only in open mineral veins where moisture can accumulate do normal signs of rock decay appear. The presence of moisture in such situations is sometimes shown most strikingly by fault-lines which are marked on the barren surface of the ground by rows of green bushes and small trees as sharply defined as hedge-rows set by the side of regularly surveyed country roads. Not only do the rugged mountain ranges of the desert disclose little rock decay, but the

[16] Bulletin of the Geological Society of America, vol. 1, 1890, p. 134.
[17] Keyes: U. S. Geological Survey, 15th Annual Report, 1895, p. 728.
[18] American Journal of Science (3), vol. xxii, 1884, p. 138.

substructure of the intermont lowlands rarely displays evidences of chemical decomposition. As a factor in the general reduction of the land surface toward sealevel, the chemical decomposition of rock-masses under conditions of an arid climate may be neglected.

In southwestern United States the floors of the intermont desert plains have been described recently[19] as often covered only to very slight depths by soil materials and as presenting almost everywhere the beveled edges of the rock strata, with little indications of rock decay. McGee[20] has called attention to similar conditions on the coastal plains of Sonora, in northern Mexico. Such conditions could hardly exist if rock decay were to go on to any marked extent.

Limitations to Geologic Work of Water in Arid Regions

CLASSES OF EROSIONAL EFFECTS

In the desert region the erosional effects of running waters may be considered under four heads: (1) General corrasive phenomena, (2) sheetflood effects, (3) arroyo running, and (4) the influence of large streams with extralimital headwaters, flowing across the arid areas through to the sea.

GENERAL CORRASIVE PHENOMENA

In the arid country the general effects of water action are made conspicuous by their absence. As I have recently shown,[21] the corrasive effects of water must be extremely impotent in a region in which the annual precipitation is less than 10 inches, nineteen-twentieths of which sinks into a porous soil as soon as it touches it. Yet these are the conditions presented by the greater part of the American arid country. The want of distinct drainage lines trenching the surface of the plains, all of which have high gradients, amply attests the deficiency of local corrasion effects through means of running waters.

It is only in the loftier mountain ranges within the arid district that there is any approach to normal corrasion by water. The mountains themselves are invariably made up of very hard and resistant rocks. With few exceptions the desert ranges are almost devoid of soil and plant growth is very sparse. The constant high winds keep the soil removed and the rocks bare. On such surfaces corrasion by water is, generally speaking, comparatively slight, as observation throughout the region

[19] Keyes: Bulletin of the Geological Society of America, vol. 19, 1908, p. 63.
[20] Bulletin of the Geological Society of America, vol. 8, 1897, p. 991.
[21] Bulletin of the Geological Society of America, vol. 19, 1908, p. 90.

clearly indicates. The relatively small volume of coarse detritus brought down from the highlands and deposited in the fans at the base further shows how remarkably unimportant is stream work. This is one of the great surprises to one leaving the humid region and entering the desert country.

ROLE OF THE PLAINS FLOOD-SHEET

In recently[22] discussing some of the effects of the desert floodsheet, I described the phenomenon as it appears on the plains—those vast noticeably inclined intermont plains of the Mexican tableland. This is the true floodsheet, as it is understood and is called by the dwellers of the arid region of southwestern United States. McGee's account[23] of the sheetflood is really a picture of "cloud-burst" effects in a desert mountain range, and the advancing flood front which this author so graphically portrays is the temporary mountain torrent debouching from a canyon and spreading out over a great fan. This phase of local flood waters is by the desert dwellers distinguished as arroyo-running. The effects of these sporadic but severe thunder-storms in the mountains and on the plains are diametrically opposed.

It does not seem advantageous to group both phenomena under a single heading, so very different are the effects of the two from each other. The floodsheet, as understood by the people of the region in which it takes place, is, as already stated, a strictly plains phenomenon. The sheetflood described by McGee is, as noted, a phenomenon of the mountains. Gradationally the first is constructive, the second destructive. The latter in its workings corresponds to normal stream corrasion in the humid land. The former in its constructive effects is merely a means of local transportation of wind-deposited dust; its corrasive powers are slight at best and usually merely accidental.

The plains floodsheet has little general corrasive effect, for the reason that the cloud-burst is of too infrequent occurrence to enable it to extensively erode the rock floor. The materials which it transports are mainly the finer soils which the winds have already drifted about over the plains. The flowing mud which marks its course is soon dried to the same pulverulent condition that it was before, and it is again carried away by the winds. The only noteworthy effects of the floodsheet is the filling of the wind-blown hollows in the surface of the plains. Thus it tends to make the plains smoother. This also accords with Passarge's observations in the South African desert plains.

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[22] Bulletin of the Geological Society of America, vol. 19, 1908, p. 78.
[23] Ibid., vol. 8, 1897, p. 87.

To the floodsheet has been ascribed the chief planorasive effects of the arid regions. The law of running waters in the desert has been thought to be contrary to what it is in a humid climate. Instead of surface waters gathering into streams, they have been regarded as spreading out into sheets. Mainly to this peculiarity of sheet-water behavior the level features of the arid landscape have been thought to be due. That these deductions are not entirely warranted by close observation of plains sheet-flood effects is conclusively shown by a number of facts.

The real reason why excessive desert waters flow down the inclined plains surface in broad sheets—floodsheets—rather than in narrow channelways, as in a normal humid country, is that the plains are already prepared as such for the flood waters. The plains were there before the waters came. The moving waters do not form the plains. The corrading effects of running waters are the same in the desert country as they are in the most humid land. The main difference lies in the fact that copious rainfall in the desert is far less frequent than in the humid region. On an average, a given locality probably does not have sufficiently heavy precipitation to form a floodsheet oftener than once in a dozen years. The gradients of the intermont plains are all ample for very effective work by water. The slopes from the mountain bases have usually at least a 2 or 3 per cent grade, and often very much higher slopes—150 to 200 feet to the mile. Besides, the middle of the plains have a pitch nearly as high. Nevertheless the plains surface remains uncorraded by the sporadic waters, for the reason that "between showers" all inroads of normal water action on the plains surface are quickly filled up and smoothed over by the drifting, wind-blown soils. A freshet gully may last a day or a week, and is then smoothed over and obliterated. It is a thousand weeks before another may be formed in the neighborhood. To the casual observer, water action on the desert is not normal, because its corrading effects are immediately and completely counteracted by the more powerful and constant wind effects. In an upraised region the normal effects of running water is to excavate trenches, ravines, and valleys; the tendency of the winds, when they can act, is to smooth over inequalities in the surface.

Were the leveling tendencies of the winds wholly absent from the desert region, it is quite probable that the corrasion effects of what surface waters there are would be much the same as they are in the humid lands, differing only in degree. This is well shown in cases where wing dams have been constructed to protect lines of railway from the disasters of the floodsheet, and the latter has come before the earthworks have had time to be leveled by the winds. In one instance in particular the culvert and track were washed out in less than an hour's time, and a canyon 75 feet deep, 50 feet wide, and several miles in length was excavated in the smooth surface of the sloping plain. By the time a permanent bridge was built to span the deep trench the winds had filled the entire excavation, so that where a yawning chasm had been was as smooth as the rest of the plain, and the wing dams alsc had melted down into the general smoothness of the desert surface. For several years, until it was finally replaced by an earthen grade, travelers were wont to express great wonderment at the possible utility of a fine iron bridge resting on the smooth sands of the desert plain.

In another instance an arroyo was partially obstructed by a wing dam composed of large boulders and a ditch cut out laterally from the low bank for the purpose of diverting over the adjoining plain some of the flood waters for irrigation. The first time the dry creek filled with water an impassable chasm 50 feet deep was cut for a distance of several miles across the plain.

As a corrasive power the floodsheet of the desert is so counteracted by the general leveling effects of the winds that its influence is as inappreciable as are the eolian effects in humid lands. The heavy sediments carried by the floodsheet often fill the hollows formed by wind scour in the surface of the plains. The only noteworthy function that the floodsheet performs is that of transporting the finer rock waste in large quantities. Even this is not so important as it at first glance might appear. The floodsheet merely carries down the plains slope for a distance of a few miles, perhaps, the wind-formed soils which, as soon as dry again, are blown back up the slope or out of the area.

The great work of the sheetflood of the desert corresponds in a humid clime merely to the movement of the idle, wind-blown sands of the seashore.

There are some phases of floodsheet effects that are of exceptional interest. A most noteworthy result of constructive work and repeated local occurrence of the sporadic "cloud-burst" on the plains is the formation of the playa. Under favorable conditions considerable sections of stratified deposits may thus form. It may be that some of the extensive Tertiary "lake" deposits of such districts as Death Valley, in eastern California, belong to this class. Another instructive result is the formation of ephemeral lakes in the deserts. At intervals of a century or two sheetflood or arroyo-running conditions sometimes prevail to an almost unheard of extent. In the Carmen bolson, in the State of Chihuahua, Mexico, unusual and repeated floodsheet waters produced a lake of large size. Still farther to the south, at Luguna, in the Sanz bolson, the floodsheet in a single night compelled the Mexican Central Railway to move its track for many miles a distance of 7 kilometers from the original line of location.[24]

ARROYO-RUNNING

The nearest approach to normal stream work in the desert country is found in the loftier mountain ranges. As the storm waters of the mountain drainageways enter the plains they quickly sink from sight. This disappearance occurs even when there are exceptionally heavy local showers. Under these conditions streams extend but little farther from the bases of the mountains than at other times. With the exception of a few days out of each year, the lines occupied by storm waters, including the liwer reaches of the mountain streams, are without water. Arroyos, or dry creeks, the Spanish-speaking people of the region call them.

To the dwellers of the arid region the running of the arroyo is always an event of more than passing notice. It has the constant solicitude of the traveler. At times of heavy rainfall in the neighborhood the dry drainageway, which in the sparsely settled districts is also often a roadway as well, becomes a raging torrent. It sweeps everything before it. Trains of gravel and boulders mark its course when it ceases flowing. The fan that it builds up at the mouth of its mountain canyon is often a mile or more across. From the point where the streamway debouches from its canyon the flood waters spread out in a broad sheet over the surface of the fan, for the latter has no deep channelways. It is arroyo-running after debouching upon the alluvial fan that McGee so well describes under the title of sheetflood erosion, rather than the action of the true floodsheet of the desert plains.

INFLUENCE OF THROUGH-FLOWING STREAMS

In the American arid region there are three large perennial rivers originating without the area that, after traversing the desert, flow through to the sea. They are the Rio Colorado, the Rio Grande, and the Rio Pecos. With the exception, perhaps, of the Colorado River, none of these streams receives tributaries in its passage through the dry region. After leaving the State of Colorado the Rio Grande, for instance, flows for 1,000 miles without notable lateral augmentation to its waters.

While these streams flowing through to the sea receive practically no additions to their volume from lateral waters within the arid country through which they flow, they have a very interesting geologic history. The huge valleys which they occupy appear to be out of all proportion to

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[24] Keyes: American Journal of Science (4), vol. xvi, 1903, p. 377.

the small amounts of water which they contain during the greater part of the year. Their gradients are high, enabling them to carry prodigious quantities of water when the snows are melting in the Rocky Mountains. Their effective erosive powers are well shown in the turbid character of their waters and the vast amounts of silt which they at all times transport.

The immediate valleys of these streams are among the most remarkable known. They extend from mountain range to mountain range on either side, a distance often of a score of miles. Their bottoms lie many hundreds of feet below the level of the general plains surface of the region. The Rio Pecos flows in a wide valley the river level of which is 1,500 feet beneath the general plains surface. The Rio Grande, which is probably the most characteristic of all of the through-flowing rivers, follows a line of old bolsons below the level of which the present bed of the stream is about 2,000 feet. The canyon of the Colorado River is a mile deep.

The Rio Grande, being typical of the large rivers crossing the desert, has received more detailed consideration than any of the others. This stream is really one of the great rivers of the American continent. It is as long as the Mississippi. Unlike the latter waterways it has, for a large river, a very high gradient. For the first 1,000 miles from its headwaters the average fall is over 5 feet to the mile. In times of flood the waters are almost of torrential nature. At certain other times of the year, as in the months of July and August, the stream is very nearly dry, although there is always a strong underflow beneath the sandy bottom.

Physiographically the origin of the Rio Grande is complex. That part of the river's course which lies in New Mexico is in the main antecedent in character. As already noted, no lateral drainage of perennial nature is received by the great stream above the mouth of the Rio Pecos. All increase in the waters of the grand stream from the sides takes place only during very brief and infrequent periods of heavy rainfall. The side waters are then torrential. At other seasons of the year these tributaries are true dry creeks, as their Spanish title appropriately signifies. These arroyos have very steep gradients, often 2 to 4 and even more feet in a hundred.

The exact rôle that the arroyos play in the general erosion of the country is not always clear. In the mountain ranges on either side of the valley of the grand stream the arroyos occupy deep canyons. In this part of their courses their channels are being rapidly cut deeper and deeper into the indurated bedrocks. After emerging from the mountains these lateral drainageways may become as pronouncedly constructive in character as they were destructive before. Into the Rio Grande channel the side arroyos no doubt pour in the aggregate large volumes of coarse mountain waste. The alluvial fans which are formed appear to become confluent, especially when the river's channel rapidly meanders. On either side of the river broad plains are thus built up, and these are inclined strongly toward the channel of the master stream. Were the river free from lateral swinging these plains would doubtless become continuous and even, like the intermont plains beyond the great valley.

The valleys of the through-flowing rivers afford a means of measurement between general desert-leveling and lowering of the country by the winds alone and general erosion by the winds assisted by stream work. The lowering of the bolsons through which these rivers flow, as compared with those without streams, seems to be about 50 per cent greater. On the whole, these trunk streams appear to transport from the region through which they pass about as much rock waste as do the Missouri, the Platte, the Arkansas, and other long rivers rising in the Rocky Mountains.

There is no doubt but that vast deflation goes on in the valleys of the through-flowing rivers. I am inclined to agree with Walther,[25] that in the walls of the Grand Canyon of the Colorado River deflative effects predominate over those of water corrasion. On the other hand, between the mouth of the Grand Canyon and the mouth of the river the cross profiles of the valley appear to be controlled more by the lateral arroyo grades. In the Rio Grande Valley this phenomenon is still more clearly displayed. The cross profile of this valley is peculiar as river trenches in general go, in that for so wide a valley it is not broadly U-shaped, but very broadly V-shaped. The controlling factor of the valley contour is the arroyo, which is a uniformly graded line from the mountains to the river's channel. In this great valley, often a score of miles and more in width to the mountain bases, water might at first thought appear to be the sole erosive agent, but wind scour operates with equal facility upon any form of surface, and its leveling influences are the same on an incline as on a horizontal plain. The profile of the valley of the Rio Grande at Socorro, for instance, is essentially as represented below (figure 2).

The Rio Grande is probably the most remarkably terraced river in the world. Bordering the stream is an extensive succession of high-level mesas that constitute the most striking feature of the great valley's surface relief. These escarpmented plains, or mesas, inclining strongly toward the river, are abruptly cut off as they near the banks of the stream. These so-called aggraded terraces I have recently shown[26] to be directly

[25] Verhandl. d. Gesellschaft f. Erdkunde zu Berlin, XIX Bd., 1892, p. 52.
[26] American Journal of Science (4), vol. xxiv, 1907, p. 467.

Figure 2.—*Profile of Rio Grande Valley at Socorro*   Distance, 40 miles

controlled by the gradients of the lateral arroyos and their varying heights to be due to the changes from time to time in the position of the river's channel. In the course of its wide meandering the river cuts rapidly into its banks on the convex side of its broad swings. In a distance of 2 or 3 miles of lateral change of channel a cliff 100 to 200 feet in height may be formed. Arroyos entering the stream from the bowed side quickly shorten their paths, assume new and higher gradients, and scoop out canyons in the old detritus accumulations. Thus between the adjacent arroyo courses there is left a "high-level" terrace, or mesa, bordering the main waterway. On the opposite side of the bow the arroyos lengthen their beds, lower their gradients, and build out new extensions of their fan plains to the water's edge. The phenomenon is best indicated by diagram of an actual cross-section of the grand valley (figure 3).

The phenomena described are repeated again and again along the whole course of the river. As a final result there are found sloping terraces at many different levels. The effects are apparently as unique as they are striking. The typical characters of the high-level plains along the Rio Grande are well displayed at many points (figure 4). At San Felipe another interesting factor comes into play. At different times during the latest geologic epoch great basalt flows have moved down the inclined plains toward the river. These have preserved the surfaces of the old mesas at several different levels. In some instances the stream has quite recently cut through the lava cap. The best description of the high-level terraces is given by Herrick.[27] Although they were thought by this observer to be striking enough to deserve the distinguishing title of clino-plains, he did not hint at their real origin.

[27] American Geologist, vol. xxxiii, 1904, p. 376.

All parts of the valleys of the through-flowing rivers traversing the desert region are deep. That they are not all narrow chasms instead of open valleys is due to the character of the substructure. With the single exception of the Grand Canyon, the valleys are all excavated in relatively soft rocks. These are mainly Carboniferous and Triassic shales, friable Cretaceous sandstones, and Tertiary marls, aggregating a very great thickness. Nowhere outside of the Grand Canyon region have any of the streams mentioned yet excavated down to the thick Paleozoic limestones and pre-Cambrian crystallines.

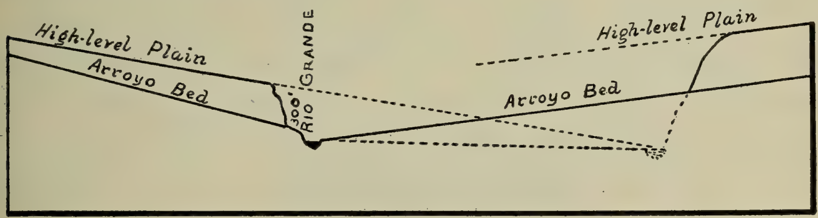

FIGURE 3.—*High-level Plains of the Rio Grande*

The influence of the hard rocks upon canyon formation is, however, suggested at a number of points other than on the Colorado. At one point, where the Rio Grande crosses from one bolson to another, the hard mountain rock between two ranges is touched. The narrows thus formed made the spot notable, for it was called by the early Spanish explorers of the region El Paso del Norte, or the North Pass. So, too, the Canadian River, where, in northeastern New Mexico, it has cut through the great so-called Dakota sandstone lying between thick shale beds, is bounded by

FIGURE 4.—*Relationship of Rio Grande Valley Terraces*

the magnificent Carrazon escarpment, 2,000 feet high, which forms the side of the valley for many miles.

The Grand Canyon region is the only place in all of the vast desert country where there has been extensive bowing up and removal of the overlying soft strata (10,000 feet in thickness). It is the only place where any one of the great streams has had opportunity to attack the crystalline basement. Were the Rio Grande or the Rio Pecos excavated from the level of the plains on either side in the basal complex instead of in soft clastics, their entire courses in New Mexico would probably now rival the inner gorge of the Colorado. Their valleys, in place of being 20 to 30 miles broad and widely open in character, would in all likelihood be not more than a mile or two in width and would be upwards of 2,000 feet deep.

The controlling gradient of the valley sides of the through-flowing streams is thus determined by the arroyo grade. The general leveling and lowering of the country takes place mainly through means of wind scour. The through-flowing rivers carry off the rock waste fully as rapidly as do the large streams of humid climates. In addition there are large volumes of rock waste and soil transported and exported by the winds.

Deflation of arid Lands

General Considerations

Although some importance has been long attached to wind as a geologic process, it is not one which the text-books on geology are accustomed to place in the front rank of earth modifying agencies. Moreover, the detailed effects of eolian activities have been chiefly considered mainly only in countries of moist climates, where water is the principal erosive force. Under such circumstances not only are the effects of wind work greatly obscured, but the real efficiency of wind as an erosive power is naturally minimized. With theoretical conditions of this kind imposed, the general rôle of the eolian influences as active and effective geologic agents has come to be regarded as quite secondary.

To be appreciated to its fullest extent the geologic work of the wind must be critically examined in regions where water action is not the most powerful of the erosive influences. The deserts furnish such favorable climatic conditions. In the arid regions, where rainfall is notably deficient, the extent and nature of constant wind scour, or eolic erosion, may be studied under conditions comparable to the study of hydric erosion in a normally wet climate. This basic feature has been in the past largely overlooked. As a result the main erosive power in the desert has been regarded as water. When water was found not to be adequate to produce the orographic phenomena, resort has been made to tectonics.

The several phases of wind work may be especially distinguished in the same way as are those of water action. The general process may be designated as eolation, a term first defined by McGee, corresponding to the water equivalent of erosion. Its subordinate activities are insolation, deflation, and aeroposition, the equivalents of rock decomposition, transportation, and deposition.

DESTRUCTIVE VERSUS CONSTRUCTIVE EOLATION

Singularly enough the work of the wind generally has been treated from the side of its constructive rather than of its destructive effects. Drifting sands of the seashore and kindred phenomena have been commonly cited in illustration. So preponderant have been the building up effects supposed to be over the denuding effects that the latter have almost invariably received scant notice. Russell,[28] along with others, has even gone so far as to explain the vast intermont plains of the Great Basin region as formed by wind-blown soils accumulating to the great thicknesses of 2,000 to 3,000 feet and more, burying the mountains up to their shoulders. This, however, is an extreme view of eolian deposition, and in the light of more recent observation must be greatly modified.

That the wind in the rôle of a general denuding power is comparable, under favorable climatic conditions, to ordinary water action in a humid climate has never received special attention. Until quite lately this phase of wind work has been passed by without exciting extended comment. Several writers have, however, recently incidentally alluded to it. Petrie,[29] for instance, estimates that along the Isthmus of Suez the country has been cut down by the wind at the rate of about 4 inches in a century. A more vigorous rate of wind excavation is described by Dwight,[30] in the Cape Cod district of Massachusetts, where in a short time sands were blown away to depths of 10 feet and more. It remained for Passarge[31] to emphasize the great denuding powers of the wind and its action as an important agent of general desert-leveling. Walther,[32] Penck,[33] and others have recognized far-reaching possibilities of wind scour, particularly in dry regions.

PLAINS-FORMING TENDENCY OF WIND ACTION

The most manifest effect of wind erosion in an arid land is the formation of plains in a manner and on a scale that finds no parallel among water-formed plains. As Davis[34] well observes, the scheme of the arid

[28] Geological Magazine, Decade iii, vol. vi, 1889, p. 242.
[29] Proceedings of the Royal Geographical Society, 1889, p. 648.
[30] Travels in New England and New York, vol. iii, p. 101.
[31] Zeitsch. d. deut. geol. Gesellschaft, LVI Bd., Protokol, 1904, p. 193.
[32] Das Gesetz der Wüstenbildung, Berlin, 1900.
[33] American Journal of Science (4), vol. xix, 1905, p. 165.
[34] Journal of Geology, vol. xiii, 1905, p. 395.

cycle is in one respect even better supported than that of the normal wet cycle, "for while the arid African plains are examples of old desert plains now growing still older, it is difficult to point out any large peneplain that still stands close to the baselevel with respect to which it was worn down."

The plains-forming tendencies of arid eolation has in the humid regions its nearest counterpart in the snow-drifting effects during a winter "blizzard." The high winds drive the hard, dry snow particles over the exposed grounds, filling the cuts of the railways and highways, ravines and gullies, hollows and low places. On the bleak hills and ridges the frozen ground is swept bare, and is often left protruding above the snowfield. In the arctic regions, where the snow is in the form of small, thick needles, rather than in the shape of flakes, the general leveling phenomena are even more pronounced. The manifest tendency in both cases is to make of an irregular surface an even plain. Were it possible to extend the "blizzard" a week or a month, or repeat it at short intervals for a longer period, instead of a single day, the general planation effects might soon be made more conspicuous, and even the eolian erosion of the hills might soon appear appreciable.

In the desert region there are the same strong winds and the same dry particles, only the latter are of soil instead of ice. Both process and material are at hand the year around. Artificial excavations are quickly smoothed over. The great systems of wing dams, or V-shaped ditches and embankments, which some of the desert railways have had constructed along the tracks to protect them against the effects of the cloud-burst and the resulting "wash-outs," are, as I have noted, soon leveled again by the driven soils.[35]

In exposed places in the desert the railway has also often erected series of high board fences as a protection against the drifting soils, after the fashion of the northern railways in winter to curb the drifting snows. At San Antonio, in the Rio Grande Valley, the loose, mobile sands and soils from off the Jornada del Muerto are, for distances of many miles, swept into the basin, forming drifts hundreds of feet in thickness, until they are finally carried away by the waters of the great stream. At San Acacia, 50 miles to the northward in the same valley, similar prodigious sand drifts occur. Many other places might be mentioned in the region where like phenomena appear. The Libyan and Nubian deserts encroach on the valley of the Nile in like manner. Only on a much larger scale, such phenomena are not unlike the drifting sands of a seashore.

[35] Bulletin of the Geological Society of America, vol. 19, 1908, p. 80.

DEGRADATIONAL CHARACTER OF DEFLATION

The denuding tendencies of deflation under conditions of aridity are of such extent that humid regions give small suggestion of their effectiveness. When a large arid area has become a plain, deflative action assumes mainly degradational proclivities. The plains have very generally rock floors, often but thinly veneered by debris and soils. In lately calling special attention to the extensive rock floor of the Jornada del Muerto, in New Mexico,[36] I noted also similar conditions existing in other bolsons of the Mexican tableland. McGee[37] expresses his surprise at finding on the great intermont plains of Sonora, Mexico, at distances of several miles from the mountains and without intervening foothills, that the horses' shoes beat on planed granite and schist or other hard rocks, instead of yielding sands. Throughout all of the American arid regions[38] the phenomenon is shown to be widespread. Passarge[39] especially describes similar clean swept plains in South Africa.

Playas and salinas also now appear to be chiefly areas of degradation rather than of aggradation, as was formerly generally believed. The manner in which playa deposits are transported I have fully explained in another place.[40]

It is the differential effects of eolative action that are most remarkable. To some of these effects attention has been already called.[41] Wind scour on the desert surface naturally wears away the areas of soft rocks much more rapidly than it does the hard rocks, in the same way as in the case of running water. After the more resistant rock-masses have been brought out in strong bas-relief eolian erosion continues to act most vigorous at the plains level, and eats back into the highlands at this horizon in the same way as does the sea on an exposed coast. The rugged seashore and its broad marine shelf has its exact counterpart in the desert in the mountain piles rising sharply, isle-like, out of a boundless sea of earth. It is the sharp meeting of mountain and plain without the usual transitionary foothills that has frequently led to the mistake of ascribing normal eolation features to faulting on a gigantic scale.

EXTRALIMITAL EFFECTS OF DEFLATION

General desert-leveling, chiefly through eolation, is doubtless much more extensive than has been commonly supposed. In the presence of

[36] American Journal of Science (4), vol. xv, 1903, p. 207.
[37] Bulletin of the Geological Society of America, vol. 8, 1897, p. 90.
[38] Ibid., vol. 19, 1908, p. 63.
[39] Zeitsch. d. deut. geol. Gesellschaft, LVI Bd., Protokol, 1904, p. 193.
[40] Bulletin of the Geological Society of America, vol. 19, 1908, p. 83.
[41] Ante, p. 581 et seq.

water action, and especially with water as the most familiar of the erosive agencies, the effects of eolation are apt to be largely overlooked. Eolation is probably an important erosive process far beyond the limits of the arid region, its influence rapidly diminishing as the annual amount of rainfall increases. For instance, the eastern boundary of the American arid region may be taken as the western line of Texas and Kansas, but eolative influences are appreciable and important so far east as the Missouri River, and even beyond.

Some observations on wind erosion have already been recorded from the Great Plains region. Winchell graphically describes the powerful effects of wind scour in the Dakotas. The possible eolian origin of the great loess deposits along the Missouri River has been recently advanced by me.[42]

The region between the arid belt and the Missouri River, known as the Great Plains, was not so very long ago believed to owe its smoothness chiefly to the fact that it was once occupied by Tertiary lakes. Later it was thought that the plains expression was largely the result of fluviatile deposition. It now appears more probable that these plains were fashioned mainly by eolation.

EXTENT AND VOLUME OF EOLIAN TRANSPORTATION

I do not know that any serious attempts have been yet made to measure the transportative powers of the winds in desert regions. As I have noted recently,[43] the effects of "dust-storms" or "sand-storms" in the arid districts in producing personal discomforture are so marked that they have commonly blinded all, even the trained scientist, to their real geologic significance. The tremendous power of the sand-storm on the Sahara and Arabian deserts have been known from earliest historic times; but it has been regarded as merely a freak of idle, shifting sands, rather than of a forceful and persistent geologic agent. Some of the geologic effects of the wind have been discussed recently by Walther,[44] whose observations were made chiefly on the northern African deserts. Similar wind effects on the bare sand bars of the Missouri River reproduce on a small scale and under humid climate the conditions of great desert regions.

The "sand-storm" of the desert is really a thing to be feared by the traveler. To be fully appreciated it has to be experienced. On the intermont plains of southwestern United States "dust-storms" are of frequent occurrence and they last several days. The volumes of soil flowing along

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[42] American Journal of Science (4), vol. vi, 1898, p. 299.
[43] Bulletin of the Geological Society of America, vol. 19, 1908, p. 81.
[44] Abhand. Königlichen Säch. Gesellschaft d. Wissensch., XVI Bd., 1891, pp. 345-570.

the surface of the ground during one of these storms must be enormous. Compared with the amount of sediments carried along by the Mississippi River in time of flood, it is estimated that in the lower 20 feet of the deflative stream there are equal amounts of rock waste moving in like cross-sections of the great river and of the air current of the desert. The air stream moves 40 miles an hour instead of 4, as in the case of the water stream, and in place of being only a mile wide, the path of the sand-storm is several hundreds of miles wide. The lower 6 inches of the air stream is almost wholly moving sand and fine gravel. The finer dust soars upwards thousands of feet, darkening the sun as by a heavy thunder-cloud. Little wonder is it that the harder rock surfaces of the desert are constantly swept clean.

After a sand-storm in the desert the changes affected excite no more attention than those after a rain storm in the moist land.

IMPORTANCE OF DEFLATIVE PROCESS

The recent observations made in the arid regions of the West point strongly to the wind as the chief erosive agent, water action having distinctly only a minor rôle in the sculpturing of the country. According to the conclusions thus reached, the wind must be regarded in a dry climate as being fully as effective in general erosion and leveling as is water in a wet climate. In the arid region wind is not only the most potent of the gradational agencies, but its efficiency as an erosive force is probably greater than all other geologic processes combined. Its main activities are strongly degradational in character; its constructional effects are local, relatively unimportant, and mainly extralimital.

In its broader effects of reducing a region to a lower plains level, wind scour is not so very unlike stream action. The less resistant rocks are removed faster than the more indurated ones, dividing the country into belts of highland and belts of lowland. The latter become plains very early in the cycle of general lowering of the land surface; the former resolve themselves into mountain ranges, finally attaining a stage of remnantal eminences comparable to monadnocks. The main difference between general leveling in a moist climate and in a dry one is that in the one the greater part of each geographic cycle is spent in attaining a plains surface which is baselevel, while in the other the plains surface is the dominant relief feature from the beginning.

Comparative Effects of Corrasion and Deflation

The origin of the mountain ranges of the Great Basin and of arid America generally has been considered mainly only from the side of pure tectonics. Basin-range structure has thus come to stand for a distinct type of orogeny. It is characterized by simple faulting on a gigantic scale, accompanied by a tilting of the fault blocks. This idea of the desert ranges is, as Professor Davis observes, a very primitive theory of mountain making and now finds little support from the studies of the principal ranges of the globe.

In ascribing to erosion an important rôle in the shaping of the Basin ranges, as some of the more recent writers on the subject have been inclined to do, stream work alone has been mainly discussed. In fact, the principles of water corrasion in a normally wet climate have been, without material modification, directly applied to the arid lands. By such procedure we arrive at an erosion scheme under conditions of aridity that are essentially the same as that of the moist climate, with this difference only, that there is somewhat less water involved. While this conception is not an unnatural deduction, when based on experience in moist countries, it does not appear to be at all congruous with the idea of actual desert conditions.

Contrary to general opinion, the most effective water action in the desert is not during the cooler portions of the year, as might be expected, but during mid-summer. July and August are the months denominated the "rainy season" by the dwellers of the arid States. Moreover, the more pronounced erosional effects of water are confined chiefly to the slopes of the loftier mountain ranges.

The intermont plains, which constitute four-fifths of the desert area, are little affected by stream corrasion. Their surfaces are rarely trenched by distinct drainageways. Their remarkable smoothness amply attests the absence of stream influence.

In general, in the desert region, where there is annually less than 10 inches of precipitation, the greater part of which sinks at once into the spongy soil as soon as it has fallen, the effects of stream corrasion are reduced to a minimum. In the mountains stream action is still an erosive factor to be reckoned with; on the plains, most of which have high gradients, it is an entirely negligible quantity.

Since in proportion as the annual precipitation diminishes the potency of the wind as an erosive agent increases, a point is finally reached, as has already been shown, under conditions of aridity, when it becomes the chief denuding influence. The full force of this observation appears to be in large measure overlooked in most considerations of the origin of the desert features. Mainly to eolian action must, therefore, be ascribed the boldness in outline of the desert ranges, the bareness of the rock floors of the intermont plains, the sharpness of meeting of mountain and plain, the complete isolation of the different mountain ranges, and the formation of the remarkable plateau plains which are so characteristic of the dry country.

Recent descriptions of desert regions by Bronhardt, Passarge, Penck, Walther, and others emphasize the wind as a potent erosive agent. Accordingly may not the great arid tracts of southwestern United States and northern Mexico be advantageously regarded as mainly sculptured by eolian action, and general desert leveling and lowering of the country viewed is carried on largely by the wind. Out of the broadly uplifted region, which had been previously profoundly faulted and folded and then planed off to the condition of a peneplain perhaps, mountain and plain appear to have been developed through differential eolian effects upon belts of alternating hard and weak rocks. Between the original plains level and the present general plains surface more than 5,000 feet of rock have been removed, leaving the more resistant mountain rock raised above the plains as rocky isles stand out of the sea.

With most of the broad intermont plains of the desert being areas of rapid degradation instead of aggradation, as shown in their remarkable rock floors, with normal water action confined to the loftier mountains, and with the plains little influenced by stream corrasion, general desert leveling and lowering must find for their chief sculpturing agents something other than stream action. All things considered, wind scour seems to be the principal erosive process in dry lands, water action very secondary. Their relative efficiencies may be roughly measured by the fact that the total volume of rock waste brought down by the storm waters from a desert range in a year may be removed by the wind in a single day. What general erosion by means of water is in a wet climate, eolation is under conditions of aridity.

Initial Physiographic Conditions of the Arid Country

GOVERNING FACTORS OF AN ARID CYCLE

The statement is made by Davis[45] that "no special conditions need be postulated as to the initiation of an arid cycle. The passive earth's crust may be (relatively) uplifted and offered to the sculpturing agencies with any structure, any form, any altitude, in dry as well as in moist regions." While as a general proposition this broad assertion might be in itself literally true, it needs strong qualification before it can be made acceptable in its entirety. The necessary consequences in the development of the arid cycle in a region like western America could hardly be as the

[45] Journal of Geology, vol. xiii, 1905, p. 382.

author mentioned has outlined. The scheme is particularly adaptable to climatic conditions characterizing a normally moist country; but the peculiarities of a dry climate are such as to indicate clearly that under the latter conditions it is not, if we are to argue for a distinctly staged arid cycle comparable to the more familiar normal cycle. Whether we have or have not such a cycle is dependent on the valuations given the several factors. Moreover, under conditions of aridity the dominant erosive agency must be of a kind radically different from what it is in the wet climate, as has been already urged.

In an arid climate, according to the author just quoted, it is assumed that the typical initial condition of the earth's surface is that of a more or less rugged and mountainous country, very much, I should judge, as we see today in the Cordilleran region.[46] In other words, the American desert country is regarded practically as having passed into its arid state very recently. In the normally moist climate, in which there is a succession of completed cycles, the most typical initial condition of the surface relief is that of a peneplain. However, instead of postulating similar topographic types for the beginnings of the normal and the special cycles, the latter is regarded as starting out under conditions of the most antithetical sort. This leads at once into difficulties many of which are unsurmountable. The selection of an antithetical type of relief instead of a normal type for the initiation of the arid cycle appears to be due largely to deductions resting upon conditions thought to obtain in the desert regions of western United States and central Asia. So far as America is concerned, there seems to be as yet very little specific exemplification brought out in support of the contention. In reality, what actually has been postulated in the Davis scheme of an arid cycle is a highly specialized initial condition in place of generalized, typical, or "no special" conditions.

Under conditions of climatic aridity the initial relief may be, for simplicity's sake, regarded as belonging to either one of two extreme types. One is a mountainous type of topography and the other the general plains type, as in the normal cycle—the peneplain, if you please. Only the first mentioned type could serve as the foundation for the distinctly marked scheme of an arid cycle, such as that recently developed by Davis;[47] the second would result in a scheme of general desert-leveling, with no distinct stages dependent on water action, as in reality is urged by Passarge.[48] As will be noted later on, illustration of the first named

[46] Ibid., p. 380.
[47] Journal of Geology, vol. xiii, 1905, p. 385.
[48] Zeitsch. d. deut. geol. Gesellschaft, LVI Bd., Protokol, 1904, p. 193.

scheme, corresponding in its several phases to those of the normal cycle, must be very rare indeed. The prevailing mode of desert leveling and lowering of an arid country must be after the fashion described for the South African region. The latter would then represent the general course of desert-leveling without marked stages rather than only the senile stage, as has been argued.

ARID CYCLE IN A MOUNTAINOUS REGION

When critically examined in the light of well known arid conditions, rather than measured by the standards of a moist climate, the evolution of a distinctly staged arid cycle beginning with mountainous relief, as outlined by Davis, is found to be merely the normally wet cycle recast with somewhat less water. The sequence of events described might extend under certain circumstances to an area of semi-arid character where both wind and water struggle for erosional supremacy, but it does not seem possible that it could obtain in a strictly desert region or a country where there is an annual rainfall below 10 inches. Moreover, the scheme mentioned postulates stream action as the chief erosive agency, while wind scour is considered only incidentally. The very reverse would seem to be true if we are to place any reliance whatever on the accounts of those who have dwelt in the desert country for any considerable length of time. In a country having the small annual precipitation mentioned, nineteen-twentieths of which sinks as soon as it touches it and does not appear as stream water at all, it is exceedingly difficult to understand how water can have the same or greater erosive efficiency that it does in a humid land.

In the Davis scheme the several stages of arid relief development do not seem to be very sharply demarked. If the periods of infancy, youth, and maturity could be distinctly made out in typical desert regions, as they are outlined, and paralleled with the wet cycle stages, their time span would be so brief and unimportant, compared with the duration of the so-called characteristics of old age, that they are altogether negligible, even when taking into account the boldest mountain relief. Beginning with a plains surface, which is not unlikely the initial character of most arid regions, such recognizable periods surely would be entirely out of question. If it be postulated that the essential characteristics of the present desert mountains of western United States, for example, are comparatively recent features, and that they were mainly fashioned subsequent to the introduction of a dry climate, as now seems altogether likely, the earlier stages of the arid period must have been very different from those depicted.

The presence of lofty mountain ranges in true desert regions very naturally gives rise, at first thought, to the impression that arid climate has come upon the region since they were upraised and their present aspects molded. Such a region as the Great Basin province, which is sometimes cited as a type of arid youthfulness, is a good illustration. That the highlands themselves may simulate the physiographic stage mentioned has been noted already as possible, since the mountains have their surfaces largely sculptured by normal water action, while the greater part of the region is still under strictly desert climate conditions.

With regional youthfulness premised, a number of incongruous conclusions necessarily follow. In the first place, the present highlands, as mere topographic features, must be regarded as mainly structural uprisings due wholly to frequent and profound differential displacement. In support of this view, the most recent investigations of a critical nature do not furnish as many facts as could be desired. A very large mass of the evidence is strongly against the acceptance of this hypothesis, which in its essence must be recognized as "practically a phase of one of the more primitive theories of mountain building that now finds few advocates in any part of the world." In the desert region the evidences against its validity are, perhaps, more obvious than anywhere else. A critical point that should alone invalidate such a theory is the fact that the mountains are composed of hard rocks and the valleys or intermont plains occupy areas of weak rocks and are in the main as truly rock-floored as the mountains themselves, rather than extensively aggraded areas.

Secondly, if the present expression of the desert ranges be considered, as urged by Spurr, as mainly resulting from extended dissection at times when the region possessed a moister climate than at present, and was, in fact, well watered, and that there was, not so very long ago, abrupt changes from humid to a dry climate, it necessitates the postulation of water action as the sole, or at best chief, erosive agency. It further postulates extensive dissection of the mountains and extensive and universal aggradation of the plains, which, as lately pointed out, does not appear always to be the case. Moreover, if there were water sufficient to accomplish results of this kind, it is, indeed, singular that so few of the bolsons have points in the rims low enough to permit the ready flow of waters from one basin to another.

Thirdly, if the lowlands, which in the American arid regions occupy four-fifths of the desert areas, be assumed to be tracts of aggradation, it is remarkable that the recent observations show conclusively that many, if not the majority, of these intermont plains have in large part at least rock floors only thinly veneered by debris and soil—a fact clearly indicating that they also are as truly areas of degradation as are the mountain areas.

As already stated, the commonly accepted inferences regarding erosion in the arid region are based chiefly upon the observations made in the loftier mountains, especially the Wasatch, the Sierra Nevada, and the southern Rockies. In these ranges the climatic conditions down nearly to their very bases are not so much those of typical aridity as they are those of a normally wet climate. These ranges may be properly considered as elevated belts of the moist land extending into the arid country. With the true desert ranges the dissection by water is not so marked.

On the theory that each intermont plain is an independent basin of initial deformation,[49] the resulting contripetal drainage system tends to make for it a separate baselevel of its own. By aggradation of a higher basin and the headwater erosion of intermittent, consequent, or subsequent streams from an adjoining lower basin, coalescence of basins is supposed to go on until there is finally a more or less perfectly adjusted drainage everywhere throughout the region. This is, of course, the necessary deduction for a normal moist country. In a region of mountainous aspect, as has been postulated for the Great Basin changing suddently to a desert country, this sequence of events might be expected were it not for the fact that very few of the intermont plains, or basins, are actually connected directly with one another by means of waterways. Moreover, it is very questionable whether in the stage having local centripetal drainage systems, the arroyos—for such all the drainageways really are—which are as discontinuous at their lower as at their upper ends, could ever accomplish a coalescence of contiguous drainage basins. I know of but few instances in all of the vast arid country in which such an interpretation could possibly be entertained.

As a matter of fact, the intermont basins have probably gone through evolutionary stages directly the opposite from those suggested. The entire region was no doubt more or less perfectly drained at the commencement of the arid period, and before epeirogenic upraising took place. Since that time deflation has separated the larger tracts into the smaller basins with no outlets. The Spanish title, "bolsons," for these basins thus acquires a technical or rather genetic and physiographic meaning of which the early explorers knew nothing. To be sure, the rims of many basins are cut by canyons which, at first glance, might appear to be capable of eventually producing a coalescence of neighboring basins. Such outlets seldom, if ever, drain an intermont plain as a whole. They usually merely cut off

[49] Journal of Geology, vol. xiii, 1905, p. 382.

from the center of a basin any sporadic waters that might come down from the inner side of the mountain rim and carry them into a lower and outside plain. This is well shown by the Tijeras Canyon, which bisects the Sandia range east of Albuquerque and which, while it would be expected to drain eventually the great Estancia Plains into the Rio Grande Valley, will probably do nothing of the kind. It merely carries off the surface storm waters from the eastern slope of the range. The Palomas Canyon, in the Sierra de los Caballos, is a similar illustration. The Southern Pacific Railway, in traversing the deserts of southern New Mexico, Arizona, and California, gives opportunity to observe dozens of like cases. The Santa Fe Railway, in Arizona and California, does likewise. Through means of deflation the soft central parts of the intermont plains are more than keeping pace with the lowering of the rims of hard mountain rock.

According to recent observations in the deserts of Nevada, California, Arizona, and Mexico, the actual levels above mean tide of contiguous intermont plains is perfectly independent of general drainage and largely also of recent deformation. This is particularly well shown in the Death Valley region.[50] It may be that the position of Death Valley itself, now 500 feet below sealevel, is as much the result of deflation as it is of tectonics; and the same may be suggested concerning the Imperial Valley, the bottom of which is below sealevel and is partly occupied by the Salton Sea.

ARID CYCLE INITIATED IN A PLAINS REGION

The descriptions of Passarge and of Bornhardt of the South African Inselberglandschaft appear to be based on the general desert-leveling effects of a surface that originally was a typical plains plateau with small contrasts of relief. These authors do not recognize a distinctly staged arid cycle comparable to the divided cycle of the moist region. It is not likely that under the conditions existing in that country there ever could be worked out a genetic scheme in the same sense as it is understood in a wet climate. In the case of the Mexican tableland and of the adjoining country of southwestern United States, the possibility of the existence of a vast plains surface, a peneplain perhaps, at the beginning of the arid period is not to be overlooked. Indeed it is probable, as already noted, that this factor must be one of the main conditions to be reckoned with.

In the initiation of an arid period on an upraised peneplain, the degradational processes, of whatever nature they may be, would be expected to start reducing the country toward ultimate baselevel just the same as

[50] Keyes: Bulletin of the Geological Society of America, vol. 19, 1908, p. 69.

under conditions of moist climate. Assuming for the moment wind scour to be the chief erosive factor, instead of water action, the broader relief features need not be so very unlike the general topographic effects produced by stream systems. In fancy, the immediate valleys of the rivers only need to be filled up. As eolation progresses the belts of hard and soft rocks would be perhaps brought into somewhat stronger contrast than they commonly are at the corresponding stage of a humid cycle. The geologic structure would be more sharply accentuated. The rock floor would be cleaner swept. The areas of weak rocks would be removed faster. At all times the plains aspect would be more strikingly dominant.

If, after the main epeirogenic movement, local orogenic activity remain quiescent, the general plains surface would continue indefinitely to persist without very marked change in original expression, excepting the accentuation of the more resistant rock belts into highlands. This appears to be the case of the South African tableland. To mark the stages of the arid cycle there would not be necessarily a succession of distinct features comparable to those of the normal cycle. Epeirogenic movement, followed by frequent and widespread orogenic disturbances and also by vigorous volcanic activity, would in a measure tend to greatly disguise most evidences of the initial aspect of a region. The same would be true of an uplifted peneplain the substructure of which before planation was more or less complicated, faulted, and folded, as appears to be the case in western United States.

Considered alone, without reference to the neighboring districts, the Great Basin presents many difficulties to a clear interpretation of some of its most characteristic features. Farther south, in the desert region at the northern end of the vast Mexican tableland, there are displayed certain phenomena which seem to offer critical testimony relative to the original aspects of the country at the beginning of the present dry cycle. A few years ago I incidentally referred[51] to the probable significance of certain remnantal plains surfaces in New Mexico as indicating an old peneplain upraised.

The general plains level is not only the dominant relief feature of the desert region, but occupies about four-fifths of the entire area of the arid country. Above it rise the numerous and often lofty mountain ranges. In the Great Basin area—which is perhaps the most familiar portion of our desert land—the two most conspicuous topographic features are not always so sharply contrasted as they are elsewhere. Moreover, in the Great Basin region the salient aspects of the country are quite different from the larger relief features of other parts of the western desert land.

[51] American Geologist, vol. xxxiii, 1904, p. 22.

There is some of the faulting that is, no doubt, more recent and more profound than elsewhere. Late orogenic movements are, perhaps, more extensive. Evidences of much greater precipitation than now at no distant geologic date are manifest. No noteworthy streams traverse the district to disguise the effects of typical desert-leveling. There are no traces of the probable nature of the surface relief prior to the commencement of the present dry cycle. The general conditions are such as to present little critical evidence in support of any of the several hypotheses that have been proposed concerning the genesis of the desert ranges.

In other portions of the desert region there are, as already noted, many features which are suggestive of structures and conditions which formerly prevailed, but of which there is small hint to be derived in the Great Basin. The most noteworthy of these characteristics are the mesas, or plateau plains, many of which now stand high above the present level of the intermont plains or general plains surface of the region. As I have shown recently,[52] these mesas manifestly represent former positions of

FIGURE 5.—*Geologic Cross-section of the Mesa de Maya, New Mexico*

the general plains surface. Their greater resistance to erosional influences and the general lowering of the country is due mainly to the protection afforded by extensive lava flows, or to hard strata, which are now the capping rocks of the remnantal levels. The surfaces on which the lava sheets rest are true beveled rock floors, just as in the cases of the present plains surface.

The most noteworthy of these elevated plains is the Mesa de Maya, in northeastern New Mexico. Its extension is the flat-topped Raton range. The greater part of this mesa is formed by a basalt plate 500 feet in thickness, resting on the beveled edges of soft Laramie shales and sandstones. The surface of this mesa is gently inclined to the eastward and extends from the Rocky Mountains, a distance of more than 100 miles, to beyond the Texas line. (See figure 5.) It is 3,500 feet above the next extensive plains level below, known as the Ocate Mesa, which in turn is 500 feet above the general plains level of the region, in this part of the territory called the Las Vegas plateau. It would appear that the Mesa

[52] Bulletin of the Geological Society of America, vol. 19, 1908, p. 75.

de Maya practically represents a Tertiary peneplain which existed at the time of the general elevation of the region. At the town of Raton its surface is now 9,000 feet above tide. Were it not for the great protecting lava field, the remnants of which constitute this plateau plain, there would today remain no undoubted traces of the old peneplain in this part of the country.[53] Probably not even a low rounded ridge would remain to mark the position of the Raton range.

That the Mesa de Maya is a remnant of what is essentially a peneplanation level which, perhaps, once extended over much, if not most, of the present desert region around the southern end of the Rocky cordillera is strongly supported by a number of facts: (1) The foundation strata, both hard and soft beds, which alternate frequently, are evenly beveled, indicating that the country at the time of planation must have been only slightly above the level of the sea. (2) The principal orogenic deformation and faulting appears to have taken place in early or mid-Tertiary times, and prior to the period of the general planing off. (3) The numerous mountain ranges of New Mexico, outside of the Rockies, are subequal in height, a fact indicating, when taking into account the period of principal deformation and faulting, the general alternation of hard and soft belts of rock, and the extent of the subsequent denudation, that the present cycle of erosion must have started with the country already more or less a well defined plain. (4) The present bilateral symmetry of the desert ranges on the whole, even in the cases of the so-called block mountains, as the Jemez, Sandia, Franklin, Magdalena, and Caballos ranges, for example, is suggestive of long continued attack by the elements upon hard mountain rock. In every one of the mountain ranges just mentioned the major fault-line, if such really exists, is as far from the crest of the mountain ridge as is the foot of the back slope. (5) Plateau plains that lie far above the present general plains level, but still below the Mesa de Maya surface, are beveled rock surfaces, protected, usually, by lava flows or hard strata. (6) With all of the present ranges of the so-called block type bordered on either side by soft beds of great thickness and the very resistant mountain strata in monoclinal attitude once extending such relatively long distances beyond the present mountain crests, it does not seem likely that general lowering of the surface of the country could have gone on so evenly without something of a plains surface to begin with. (7) The postulation of a general mountainous surface at the beginning of the present geographic cycle, as represented by the Mesa de Maya planation surface, finds many incongruities which need not be dwelt on at this time.

[53] Keyes: Proceedings of the Iowa Academy of Sciences, vol. xv, 1908, p. 221.

The evolution of an arid cycle from initial conditions of a plains surface, analogous to the peneplain of the humid cycle, and without material aid from running water, give land forms something as represented in outline in the subjoined diagrams (figure 6). Contrasted with the geographic features of infancy under conditions of a humid climate, the first excavations are, instead of deep V-shaped channelways in the old peneplain, broad, plain-like valleys (figure 6*a*). The best example, perhaps,

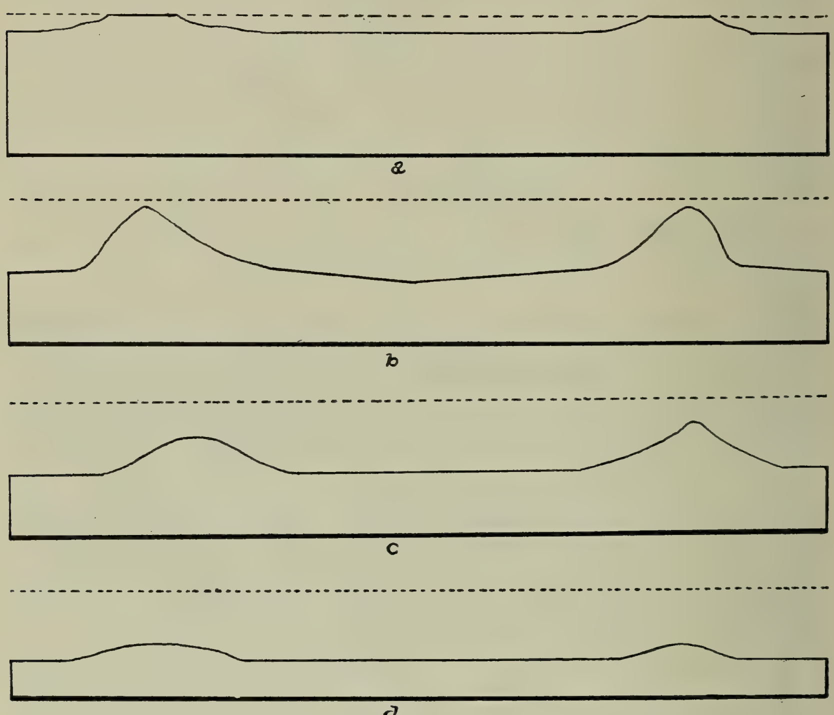

FIGURE 6.—*Profile of Arid Physiographic Stages*

in the American arid country is in the Raton Range. There are other plateau plains in the region where, on account of vast outpourings of lava, deflation has lagged behind the general lowering of the country and where the earliest inroads of erosion are now taking place. In this connection the Chupadera Mesa, in central New Mexico, may be noted especially.

Arid youth I take to be typically expressed in the northern part of the Mexican tableland, including central New Mexico and southeastern Arizona. The general plains surface is now a mile above sealevel, and the desert ranges rise still another mile. The mountain ranges are sharp in outline; the intermont plains broad and usually rock-floored (figure 6*b*).

The Great Basin region appears to have reached the stage of arid maturity. Recent volcanic outpourings have greatly disguised many portions of this vast area and have occasioned a puzzling medley of relief features. The older elevations, represented by such mountains as the Charleston, Vegas, Kingston, and many other ranges of Nevada, are now relatively low and rounded in outlines (figure 6*c*). In this region it will be important to separate the older general desert lowering features from the later aspects imposed by local volcanic and orogenic disturbances before the real physiographic expression can be clearly grasped.

Of desert old age, Davis cites the South African region. In our own country, in the vast Colorado plateau, with its greatly subdued surface features, we seem to have a good example of arid senility (figure 6*d*). Owing to the low dome-shaped structure, the higher and weaker strata have been quite generally stripped off, leaving the more resistant Paleozoic rocks exposed in great stratum planes, little modified by differential erosion. The through-flowing Colorado River introduces the exotic element of vigorous corrasion in this area whereby the broader aspects of general desert erosion and the immediate effects of eolation are greatly obscured.

Recapitulation

In the foregoing consideration of the desert region two features in particular are emphasized: The dominancy of deflation among the general erosive agencies and the probable plains character of the surface of the country at the beginning of the present dry cycle. The conclusions reached are that:

1. The corrasive work of water is, in all desert regions, much less effective than is commonly supposed, and is of about as much importance as is wind action in a humid land.

2. The sheetflood effects are unimportant as lasting erosional phenomena and they are largely counteracted by the action of the winds. Their main function is merely the filling of wind-formed hollows in the plains surface, thus making the latter all the smoother.

3. Arroyo-running, occurring at infrequent intervals, is the nearest approach to normal water action, but its main corrasive influence is confined to the slopes of the higher mountains, its effects upon the plains being very slight.

4. The few large through-flowing rivers which traverse the arid region do not form an integral part of it. They merely cross the dry country

on their way to the sea, having their origin outside of the area. Probably their presence has tended more than any other one factor to prevent a proper and early understanding of desert erosion.

5. In the arid region eolation is the chief gradational power to be reckoned with, and its actual potency is probably far greater than water erosion under the most favorable conditions. The characteristic aspects of the entire desert landscape are to be mainly ascribed to the peculiarities of deflative sculpturing powers.

6. Deflative action is chiefly destructive in character; its constructive effects, at least within the boundaries of the dry country, are ephemeral and relatively unimportant. The clean swept rock floors of many intermont plains clearly indicate that the latter are areas of constant denudation rather than of great aggradation, as has been generally supposed.

7. The general relief tendency of deflation is preeminently plains-forming. From first to last of the geographic cycle in an arid climate the plain prominently persists.

8. In the arid region of western America a thickness of no less than 5,000 feet of rock has been removed in attaining the present plains level. This vast amount of excavation seems to be largely the work of the winds alone. The process is going on today as actively as it has at any time in the past. It is probable that the general lowering of the desert country is much more rapid than that of general stream corrasion toward base-level in a humid land.

9. The American arid country was at the beginning of the present geographic cycle essentially a peneplain recently uplifted. This conclusion is believed to be amply attested by the great remnantal plains which are still found standing high above the existing plains surface. Above the latter more than 4,000 feet rises, for instance, the unique Mesa de Maya. The numerous plateau plains of the dry region appear to have a like significance.

10. The evolution of the present relief expression of the desert country is not believed to be from a surface initially of rugged mountainous topography and through the sculpturing agencies of running water, but is thought to be from a plains surface through eolation principally.

11. The origin of the Basin ranges and of the desert ranges generally is, therefore, regarded as due in the main to extensive and vigorous differential deflation on a region that had been previously flexed and profoundly faulted and then planed off, bringing narrow belts of resistant rocks into juxtaposition with broad belts of weak rocks, the former now forming the desert highlands and the latter the desert lowlands, or intermont plains.

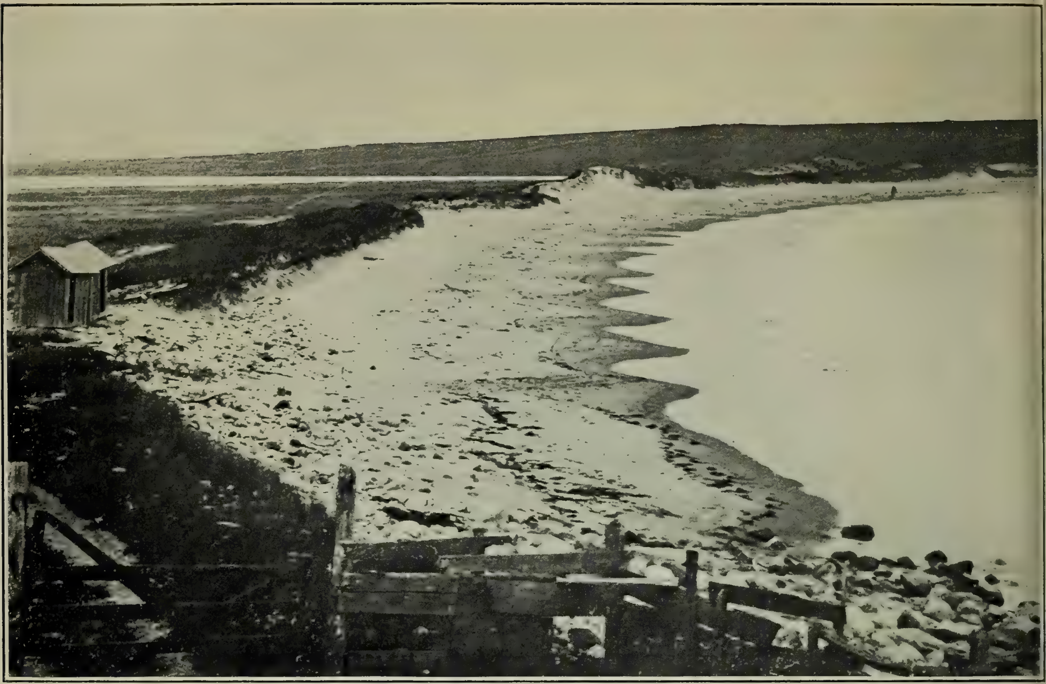

FIGURE 1.—SAND BEACH CUSPS ON WESTQUAGE BEACH, RHODE ISLAND
Photograph by Sharples for the U. S. Geological Survey

FIGURE 2.—COBBLESTONE BEACH CUSPS ON WINTHROP BEACH, MASSACHUSETTS
The cusps are partially eroded. Smaller cusps more closely spaced are forming at water's edge

BEACH CUSPS

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BEACH CUSPS[1]

BY DOUGLAS WILSON JOHNSON

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"Selecting any pebbly beach where the stones are prevailingly of small enough size to be readily tossed about by the waves, the observer will note that at almost all times, but especially after a heavy storm, the slope from the high-water mark downward is scalloped in a curious manner. From the level beyond the waves, ridges tapering outwardly extend down the incline, it may be, for a distance of ten to fifteen feet or more, and a height of from a few inches to two or three feet. Between these ridges, which taper toward their lower and outer parts, there are small, wedge-shaped embayments, which at the outer edge of the ridges may be from two or three feet to fifteen or twenty feet wide, tapering thence, like the section of a rather pointed cone which is obtuse at the apex, to the edge of high water. These scallops may, under favorable conditions, be traced in orderly and uniform succession along miles of shore."—N. S. SHALER, 1895.

INTRODUCTION

The purpose of this paper is to review such previous accounts of beach cusps as deal with the origin of these forms; to describe in some detail

[1] Manuscript received by the Secretary of the Society April 8, 1910.

the characteristic features of the cusps; to examine the theories which have been proposed to explain their origin, and to offer a theory which differs in some essential particulars from those already advanced.

Beach cusps are of common occurrence along most shores, but are of no great significance to the geologist or geographer. The writer's apology for what may seem an over-elaborate treatment of an unimportant topic is that he found the detailed study of the cusps an interesting occupation during vacation hours, and gained from the study some points of more than passing interest.

Literature

In an unpublished thesis, "The Geology of Nahant," written by Prof. A. C. Lane about 1887, the cusps on Lynn Beach, Massachusetts, are briefly described and their origin discussed. Lane concluded that cusps are formed by the action of waves parallel to the coast; that they have their beginnings in accidental irregularities on the beach; that they become evenly spaced as the result of some process of adjustment not clearly understood, and that the distance between cusps is in some manner related to the height of the waves and the breadth of the beach. This brief unpublished account of cusps was not brought to the writer's attention until after the following pages were written. As will appear later, his conclusions agree with those reached by Lane in important particulars. A short abstract of this thesis was published in 1888.

Prof. N. S. Shaler, in his popular treatise, "Sea and Land" (1894), gives a clear description of the curious "ridges and furrows" occurring on shores, recognizes their temporary character and the ease with which they are obliterated by wave action, and expresses the opinion that "the origin of these peculiar structures is not easily accounted for" (57). A year later Professor Shaler published a somewhat fuller account of beach cusps in his paper, "Beaches and Tidal Marshes of the Atlantic Coast," from which the quotation at the beginning of this article is taken. A theory of origin was proposed in the following words:

"It seems to the writer that these scallops were formed about as follows: In a time of storm the inner edge of the swash line formed by the body of water which sweeps up and down the beach has a very indented front, due to the fact that it is shaped by a criss-cross action of many waves. As these tongues run up the beach and strike the pebbles, they push them back so as to make a slight indentation where each tongue strikes. As the water goes back, it pulls out the fine material, but does not withdraw the pebbles. The next stroke of the splashing water then finds a small bay, the converging horns of which slightly heap up the fluid, making the stroke a little harder in the center of the tongue and excavating the bottom of the bay still further. As the reentrant grows larger and the tide rises higher, the water, as it runs up, forms a small wave, which breaks on the shore of the recess and casts the pebbles more into the form of a ridge. This action, continuing for some hours before the tide turns, serves to shape the embayment.

"It should be carefully noted that, when the swaying waters rush up into the shore scallops, the converging walls of these indentations deepen the current and add to the efficiency of its movements—a process which is essentially like that which is brought about when an ordinary wave enters into a recess of the cliff, or the tidal undulation is crowded into an indentation such as the Bay of Fundy."

In his paper, "Sea-beaches and Sand-banks" (1898), Vaughan Cornish briefly refers to the "succession of ridge and furrow at right angles to the sea-front," and attributes the phenomenon to the erosive action of waves which are increasing in size and attempting to reduce the beach slope to a gentler gradient (637).

One year later (1899) Prof. M. S. W. Jefferson published a paper in which he described some of the characteristic features of beach cusps and offered an explanation of their origin. Jefferson's studies were "made at a single beach (Lynn Beach), though confirmed by some observations from Gay Head and Narragansett Bay." He concluded that the cusps were caused by the escape of water from behind a barrier of seaweed located near the upper zone of the beach. Occasional waves of more than average size overtop the seaweed barrier and leave large quantities of water imprisoned behind it. After the retreat of the wave the imprisoned water escapes through occasional breaches in the barrier and flows down the beach in streams of considerable strength, which scour away the beach material along their courses. The residual masses of material thus left between the stream lines are gradually shaped by the waves into typical beach cusps. A stony barrier would probably not operate in the same manner as a barrier of seaweed, since the water would filter through the mass rather than wear channels. "It would seem to follow that such stony cusps are to be looked for only on coasts where seaweed or some similar material is abundantly thrown up."

In 1900 Prof. J. C. Branner published a paper entitled "The Origin of Beach Cusps," based on observations made on the California coast and the northeast coast of Brazil. He noted the fact that cusps occur where "there are no seaweeds or other 'drift' on the beach," and concluded that they are formed "by the interference of two sets of waves of translation upon the beach." The accompanying diagrams, reproduced from Branner's paper, will serve to make his theory clear. In figure 1 "the concentric lines represent two sets of waves advancing on the beach in the direction indicated by the arrows and crossing each other along the broken lines. In deep water these are waves of oscillation, but when they reach the shallow water on the beach they become waves of translation and interfere with each other where they converge upon the shore. The tendency is for them to check each other along these lines of interference and to heap up the sands at the points marked A, where they strike the beach. At the points marked B the waves diverge and throw the beach sands and all floating material alternately right and left."

"In figure 2 the waves are represented as breaking on a straight beach. If the water offshore were of a uniform depth and the waves were evenly spaced, the cusps in this case would, for obvious reasons, be further and further apart from left to right, as shown along the beach D E. The

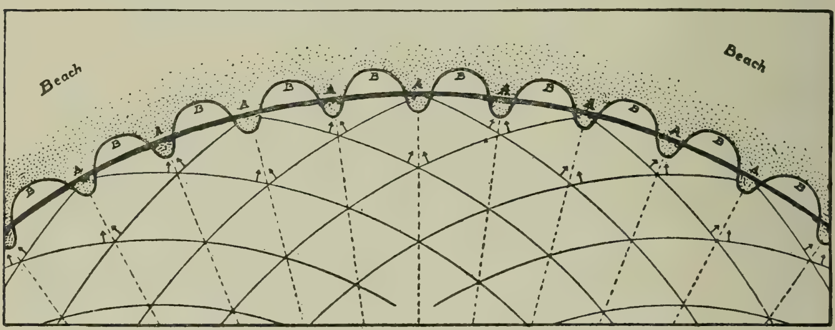

FIGURE 1.—*Diagram illustrating the Formation of Beach Cusps*

The concentric lines represent two sets of wave crests. The heavy line is the curve of a beach which, with these waves, would yield cusps of uniform size. (After Branner.)

distance between the cusps is equal to the spaces measured on the beach between the radii along which the wave interference approaches the shore."

In an editorial note in the Journal of Geology for 1901, Professor Branner briefly restates his theory of cusp formation, and calls attention to the fact that the "giant ripples" and similar beach structures observed in sedimentary rocks may be fossil beach cusps.

Among the "author's abstracts of papers read at the Washington meeting of the American Association for the Advancement of Science, Section E," published in the Journal of Geology for 1903, is an abstract of a paper by Professor Jefferson entitled "Shore Phenomena on Lake Huron." The abstract suggests a modification of the author's views as published four years before; for while in the earlier paper the possibility of a stony barrier's playing the same part in cusp formation as a seaweed barrier is considered and rejected as improbable, in the later paper we read that the cusps are "component features of a *beach ridge*, . . . The ridge . . . has at times been seen and photographed with water caught behind and rushing out at breaks in the line, as with the weed line at Lynn." Whether or not the breaking of water through the barrier is still thought to originate the cusps is not made clear. The cross-waves noted by Branner were observed by Jefferson, but at no place did he find such waves associated with cusp formation.

In his paper, "Cuspate Forelands along the Bay of Quinte" (1904), Dr. A. W. G. Wilson describes the occurrence of "cusplets" on one of the forelands, and ascribes them to the action of a single series of waves striking the beach at an oblique angle. Although Doctor Wilson does not refer to the previously published accounts, and although the very

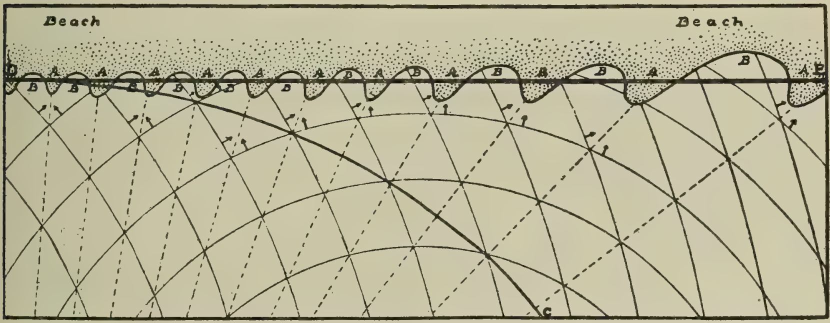

FIGURE 2.—*Diagram illustrating the Formation of Cusps*

The cusps of different sizes are formed on a straight beach, D. E. If D C were the beach line, these waves would produce cusps of uniform size. (After Branner.)

asymmetrical forms described by him differ in some respects from the essentially symmetrical features generally known as beach cusps, there is little reason to doubt that the former are modified phases of the latter.

In 1905 Professor Jefferson published a paper entitled "On the Lake Shore," in which he gives a brief account of beach cusps, and says "they never occur except after waves that have played squarely on shore." Examples which must have formed without the aid of a seaweed barrier are figured, but their origin is not explained. In referring to one particular set, however, Jefferson classes them with the Lynn beach cusps, and says: "Some high wave surmounts the ridge, here of sand, there of seaweed, and its crest water is ponded behind it to escape by any sags that may occur in the line."

The writer's attention was directed first to the cusps in the fall of 1903. At the New York meeting of the Association of American Geographers in December, 1906, he presented a paper, "The Origin of Beach Cusps," in which it was pointed out that cusps may be produced, both naturally and artificially, by a single series of waves parallel to the beach, uninfluenced by seaweed or other accumulations. On the basis of further observations and experiments, the origin of beach cusps was again discussed at a meeting of the geologists of the northeastern United States held in New York, April, 1908. An abstract of this communication appeared in Science the following October.

Before considering theories of origin, it is desirable to set forth in some detail the characteristic features of the cusps.

Characteristics of Beach Cusps

Contributing Observers

In order to secure careful observations of cusps under as great a variety of conditions as possible an outline of the points concerning which information seemed desirable was prepared and given to a number of friends, who offered to record observations. In this way my work has been supplemented by contributions from the following persons relating to the localities mentioned: Prof. W. O. Crosby, Nome Beach, Alaska; Prof. A. W. Grabau, beach south of Dyker Heights, Brooklyn, New York; Prof. H. W. Shimer, Winthrop Beach, near Boston; Mr. T. I. Read, E. M., Virginia Beach, Virginia; Mr. James T. Kemp, beach near Huletts Landing, Lake George, New York; Miss M. E. Blodgett (then a student in geology at the Massachusetts Institute of Technology), Lynn Nantasket, and other beaches in the vicinity of Boston. To all these my thanks are rendered. My own observations have principally been made on Marblehead Neck, Lynn, Revere, Winthrop, and Nantasket beaches, near Boston; Westquage Beach, Rhode Island; the beach south of Dyker Heights, Brooklyn; several beaches near Hulett's Landing, Lake George, New York; beaches along various small lakes and ponds, and the artificial beaches referred to below.

Among the points specified on the blank forms prepared as guides to the observation of beach cusps were the following: Locality; general description of beach; length of cusps; distance between points of cusps; size of cusp material; relative steepness of two sides of cusp; position of cusp axis relative to shoreline; slope of beach; comparison between beach material and cusp material; whether or not cusps were being fashioned at time of observation; any evidence of long-shore current; height of waves; evidence of more than one set of waves; whether or not waves come in parallel to beach; direction of wind; stage of tide.

The following description of beach cusps is based largely on my own observations, but is corroborated by the accounts furnished by others:

FORM

When most perfectly developed, the ideal beach cusp has a shape suggesting an isosceles triangle, and is so placed that the unequal side (hereafter called the base) is parallel to, but farthest from, the shoreline. The "triangle" may be short and blunt, or may be so greatly elongated that the two equal sides extend far down the beach and finally unite to form an acute point (hereafter called the apex). These same sides may

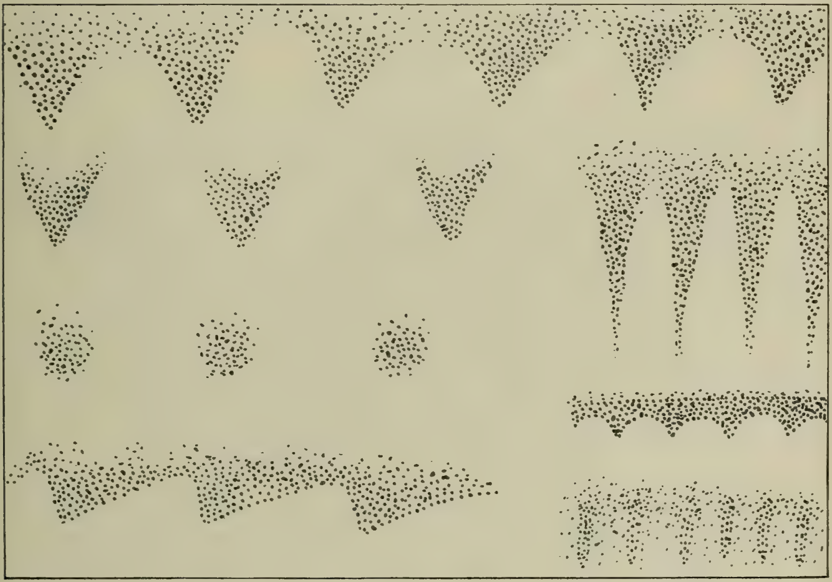

FIGURE 3.—*Variations in the Form of Beach Cusps*

be relatively straight, but are more often concave, sometimes convex, outward. The actual variations in form are numerous and wide (figure 3). Every gradation can be found from well developed triangular accumulations of sand or gravel to widely spaced heaps of cobblestones of no definite shape. The cusps may constitute the serrate seaward side of a prominent beach ridge, or may occur as isolated gravel hillocks separated by fairly uniform spaces of smooth sandy beach. They may be sharply differentiated from the rest of the beach, or may occur as gentle undulations of the same material as the beach proper, and so be scarcely discernible as independent features. Indeed, the variations in beach cusps are so great that their form is often not as sure a guide to their detection as is their systematic recurrence at fairly uniform intervals. One or two indefinite heaps of gravel on a beach would escape notice, but a hundred such heaps, evenly spaced, attract attention.

A cusp may rise from an inch or less to several feet above the general level of the beach. Many are relatively low and flat, others high and steep-sided. Sometimes the highest part is comparatively near the apex; at other times the highest part is far back, and from it a long, sloping ridge trails forward toward the water. As a rule, the cusps appear to point straight out toward the water—that is, the axis of the cusp is at right angles to the shoreline—and neither side of a cusp is steeper than the other, except where oblique, wind-made waves have eroded one side only, a condition observed in a few cases.

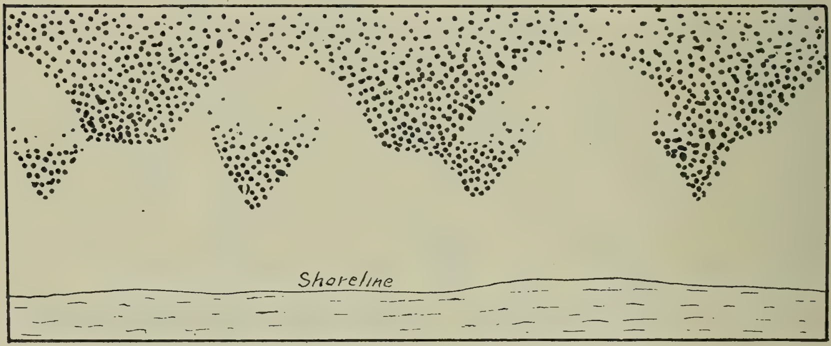

FIGURE 4.—*Partially eroded older Cusps and respaced later Series*

An interesting variation in form is found where old cusps terminate abruptly in little "cliffs" instead of in sharp points. It is plain that after the old cusps had been formed they were cliffed by waves under changed conditions and their apices cut away. From this eroded material later series of cusps may form, unrelated in position to the original series. Figure 4 represents a case of this kind as observed in cobblestone and gravel cusps on a gravel beach at Winthrop. Sometimes the cusps are more completely eroded than in the case figured, and remnants of three or four distinct sets, of different sizes and spacing, may often be observed on a beach at one time.

MATERIAL

As in the form of cusps, so in the material of which they are composed, is there the widest variation. In building them the waves make use of everything, from the finest sand to the coarsest cobblestones.

There is no necessary relation between the size of the cusp and the size of the material of which it is composed. Large cusps built wholly of fine sand are reported from Virginia Beach, and still larger ones (20 to 30 feet from apex to base and 75 to 90 feet between apices) built of similar material were observed on the beach south of Dyker Heights. The largest examples are more often built of coarse gravel or cobblestones, while small ones may be composed of either fine sand or coarse gravel. The very smallest cusps (a few inches in length) consist of fine material only, since the small waves which build them can not transport coarse gravel or cobblestones. Where both coarse and fine materials occur on a beach, the cusps are built of the coarse material. Gravel cusps on a sandy beach are of common occurrence, but I have not observed sand cusps on a gravel beach.

SIZE

The smallest cusps which have come under my obesrvation have been those artificially produced in the laboratory. These have varied from an inch to several inches in length, measured from apex to base. Some almost as small are to be found along the shores of sheltered ponds. On a sandy beach at the head of a protected bay south of Huletts Landing, Lake George, cusps from 8 to 12 inches long were formed by the small waves set in motion by a gentle breeze. Those found along the seashore may reach a length of 30 feet or more. It should be noted, however, that the length measured from apex to base is less significant than the distance between cusps, measured from apex to apex; for while it is a general rule that the farther apart the cusps the larger is their size, some which are closely spaced may be greatly elongated, as pointed out above, and this elongation appears to be the result of rather accidental conditions, and to have no great significance. Measurements across the bases might be more significant, but it is often difficult to determine the length of base, as when the cusps form part of a beach ridge or constitute widely separated heaps of gravel having a vague shoreward boundary. However, enough has been said to give some idea of the range in size; and although size is in some degree related to spacing, the latter is the really important factor, as noted below.

SPACING

The very small cusps made in the laboratory are from one to several inches apart, measured from apex to apex. On the shores of small ponds, bays, etcetera, where only small waves are developed, the spacing varies from less than a foot to two feet or more. On sea beaches the cusps built by small waves may be less than 10 feet apart, while those built by large storm waves may be 100 feet apart.

Jefferson emphasizes the lack of regularity in the spacing of cusps, whereas others have been impressed by their regular recurrence at fairly uniform intervals. Inasmuch as the matter of spacing is of vital importance in any discussion of the origin of these forms, we may examine it somewhat carefully. Jefferson writes (1899, 238): "The constant *recurrence* of bay (intercusp space) and point (apex) as one walks along the beach suggests that there is a regularity in the width of intervals. This is not so, however, on Lynn Beach, as appears from the diagram, measures from point to point along the beach being 21, 20, 18, 16, 22, 17, 6, 7, and 22 paces. Fainter cusps farther south toward Nahant show similar irregularity. It might be said, however, that on Lynn Beach they are commonly about 20 paces wide." And again (1905, 10): "In a view

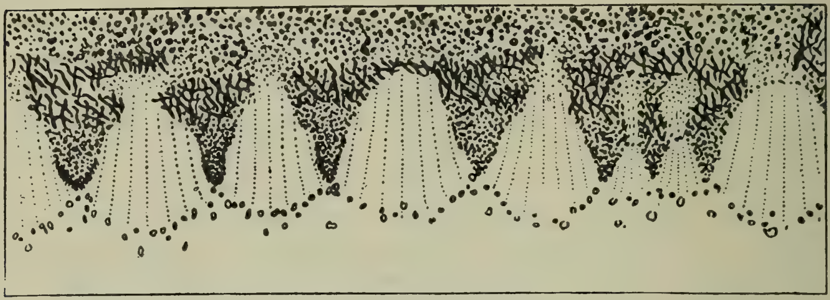

FIGURE 5.—*Beach Cusps (after Jefferson) showing compound Cusps*

along the beach these unevennesses are foreshortened into the appearance of points of sand or gravel known as beach cusps. They are less even than they look." In still another connection (abstract of paper presented before the Geological Society of America at the Boston meeting, 1909) he says: "Perspective foreshortening gives them a fictitious appearance of regularity." On the other hand, Shaler (164) speaks of their "orderly and uniform succession," and it has seemed to me that the degree of regularity in spacing is so great as to be incompatible with certain of the proposed theories of origin.

It is true that measurements of the spaces do not always give exactly the same figure; that in the early stages of development a greater degree of irregularity prevails than later on, and that even where cusps are very perfectly developed, occasional aberrant features obscure the regularity of spacing. Nevertheless, a large number of observations of beach cusps in all stages of formation and destruction and the production of artificial cusps in the laboratory have convinced me that a fairly high degree of regularity in spacing is a most characteristic feature of well developed forms and must be carefully considered in any attempt to account for their origin.

An inspection of the figures quoted above from Jefferson, or, better, of the diagram (figure 5) to which he refers, shows one of the aberrant features which sometimes obscure the regularity of spacing. This consists of a compound cusp having three apices, between which are included the abnormally small spaces of 6 and 7 feet respectively. Unless the conditions of wave activity changed, the compound cusp would eventually be fashioned into two normal cusps by the destruction of the central pex, possibly accompanied by an enlargement of the space thus gained until it more nearly corresponded in size to neighboring spaces. Thus the only pronounced irregularity in Jefferson's figures represents a temporary failure of the waves to complete the approximate equalization of inter-cusp spaces. The following figures illustrate the spacing as measured on four different beaches. Successive figures denote the number of paces to successive cusps.

I

31 – 35 – 35 – 34 – 33

II

12–12–11–10–12–13–10–10–11–9*–8*–13–15–11–10–10–12

III

9–9–7–7–8–9–10–7*–9*–10–8–6*–7*–7–6–6–6–6–4–5*–5*–5–7

IV

28–28–28–27

V

11–11–11–5 †

VI

17–17–15–9–17–15

VII

14–19–17–18–13–12–12–15–15

VIII

27–27–30

IX

13–13–19

X

6–7–7–8–6

I. Sand cusps on beach south of Dyker Heights, Brooklyn. A. W. Grabau and D. W. Johnson.

II and III. Older and later cusps observed at same time on Winthrop Beach. D. W. Johnson.

IV and V. Older and later cusps observed at same time on Pond Beach, Nahant. M. E. Blodgett.

VI and VII. Cusps on small beach near Nahant; observed at different times. M. E. Blodgett.

VIII, IX, and X. Three sets of cusps observed on upper, middle, and lower parts of Pond Beach, at same time. D. W. Johnson. The number of measurements is small, but represents the degree of variation in spacing.

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* Part of compound cusp. † Imperfectly developed.

It will be noticed that in series II and III the intervals between the older cusps on the upper part of the beach are never less than ten paces, except in the case of one triple-pointed compound cusp, while the intervals between those formed later, farther down the slope of the beach, never exceed 10 paces. The intervals in series IV are always more than double those in series V on the same beach. In the three series, VIII, IX, and X, observed on the same beach at the same time, the smallest interval in VIII is larger than the largest in IX, and the smallest interval in IX is larger than the largest in X.

It is evident from the above figures that a certain degree of regularity is manifested in the spacing of the cusps. In any given series the spaces vary within certain limits, but seldom fall below or rise above those limits unless the associated cusps have a noticeably abnormal form. No theory of origin is tenable which does not recognize and account for the significant degree of regularity indicated by these figures.

The length of the intercusp spaces varies with the size of the waves. When the waves are about an inch in height the cusps are from 3 to 9 inches apart; when the waves are from one and a half to two and a half feet high they are 30 to 60 feet apart, while large storm waves build cusps 100 feet or more apart. These figures are only approximate, and are based on rough estimates of the wave height close to the shoreline. Sufficient data have not been secured on which to base a reliable determination of the precise relation of intercusp space to wave height, but within certain limits there is a suggestion that doubling the wave height doubles the length of the space. A large number of careful observations would probably establish this point. In conducting such an investigation the observer must satisfy himself that the waves he sees are actually building the cusps, for waves of any size may play about cusps formed by other waves of different size, and thus mislead one who compares the intercusp spaces with the height of the later waves. Fortunately waves of a given size do not long leave unmolested a series of cusps formed by waves of an entirely different size, and the patient observer can in time determine whether or not the waves then breaking on the beach are to be correlated with the cusps at the water's edge.

This brings us to the consideration of another significant point in connection with the spacing of beach cusps, namely, the relative ease with which old cusps are remodeled by waves differing in size from those which formed them. If closely spaced cusps formed by small waves are attacked by larger waves, there ensues a rearrangement by which the cusps become larger and farther apart. This rearrangement may be gradual, and may be accompanied by the combining of some cusps and the slow obliteration of others; or if the new waves are very large, there may be a rapid obliteration of the earlier series of cusps, followed by the slow formation of a new series adjusted to the size of the later waves. If the widely spaced cusps formed by large waves are attacked by smaller waves, so much of the older cusps as can be reached will be eroded and the material refashioned into smaller cusps more closely spaced, regardless of the positions of the older ones (figure 4). When large and widely spaced cusps are built by high storm waves well up the slope of the beach, only their apices are apt to be attacked by the smaller waves of calmer weather, and so it happens that we commonly find the largest cusps partially preserved near the top of the beach, with series of smaller and more closely spaced cusps farther down the slope.

Regarding the building of beach cusps, Jefferson writes (1899, 246): "If it be asked how this begins, the answer must be that the beginning is as old as the beach. . . . Each set of cusps may modify its successors. A new crest of seaweed flung up today is likely to have its weak points in some measure determined by the previous channels. In violent storms it is doubtful if this control is significant. Each storm probably sets the shape in which the waves must play for a long time." If we accept Jefferson's theory of cusp formation, the conclusions just quoted would seem to be reasonable. But the sensitiveness of beach cusps to changes in size of waves leads to quite opposite conclusions. Instead of the beginning of cusp formation dating back indefinitely, there appears to be a new and quite independent beginning with every marked change in the size of waves. One set of cusps seems to have little influence on the position of its successors. Along the shores of a little bay just south of Huletts Landing, Lake George, cusps built by small waves are completely obliterated each day by three or four of the large waves which strike the beach after the passing of a steamboat. Opposite the cusps, but farther up the beach, pegs were driven to mark the position of the cusps. After their obliteration they formed again under the influence of the small waves, with the same size and spacing as before, but, as shown by the pegs, in totally new positions. The law controlling the relation of spacing to wave size was operative, but the cusps which were there a few moments before did not determine the position of their successors. The same phenomenon may be observed in the production of artificial cusps. Furthermore, if a series of parallel trenches be excavated in the artificial beach at right angles to the shoreline, the intercusp spaces and the cusps will not correspond with the trenches and intervening ridges which have been made to guide wave action. In fact, waves of a given size insist on forming cusps at appropriate intervals, and while their action may be influenced within certain limits by natural or artificial trenches on the beach, they refuse to be controlled by such depressions unless these are themselves appropriately spaced.

RELATION OF CUSPS TO OTHER BEACH FORMS

A strongly marked ridge of sand, gravel, or cobblestones rising above the general surface of the beach, and known as the beach ridge, is a well recognized product of wave activity. The bases of the cusps may merge with this ridge in such a manner as to leave no doubt that they constitute an integral part of it. The ridge may or may not be breached opposite the intercusp spaces; but it should be noted that with the progressive concentration of the water in the intercusp spaces, which converge shore-

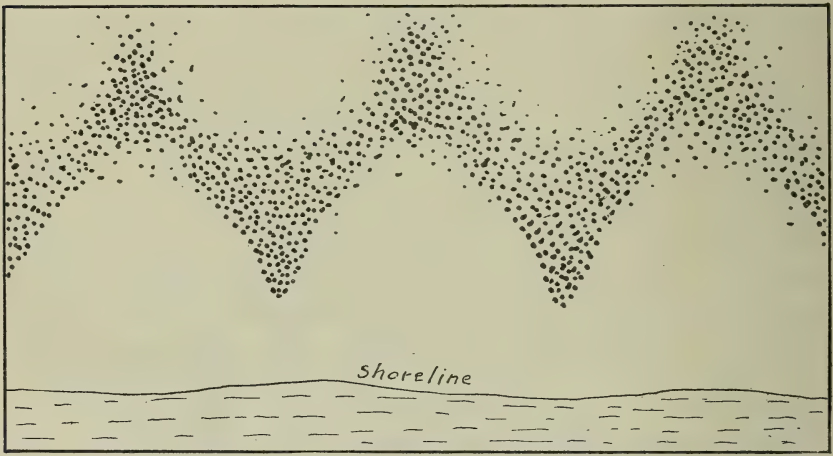

FIGURE 6.—*Normal and inverted Beach Cusps*

ward, the parts of the ridge most likely to be broken through are the parts opposite these spaces. It is, therefore, not necessary to regard the intercusp spaces as the product of erosion by water which was imprisoned back of the ridge and broke through it, either at the lowest places or at points of weakness. Conclusive evidence that the ridge may be breached from the seaward side is found in the gravel or cobblestone deltas which are sometimes built *landward* from the gap in a ridge at the head of an intercusp space (figure 6). It seems clear that the water concentrated between cusps broke through the ridge and carried gravel and cobbles into the area back of it. In one case observed at Nahant the landward projection of cobblestone accumulations was so systematic as to give a series of "inverted cusps" alternating regularly with the beach cusps proper. The breaching of the ridge by water confined between previously formed cusps has been repeatedly observed in the laboratory experiments.

There are abundant instances of cusps unrelated to any beach ridge. Cusps of gravel are often formed at widely separated intervals with smooth, sandy beach between; the points of old cusps are nipped off and respaced without the development of a ridge. One must conclude that cusps may develop as the serrate seaward margin of a beach ridge and may determine the places where it will be breached by the waves, but that there is no necessary relation between the two.

The return current of water flowing down the beach after the wave has ended its advance, sweeps seaward more or less fine material which is fashioned into a deposit analogous to a delta; but since the current which transports and finally deposits this material has, despite its very short length, an almost indefinite width, the deposit is not shaped like the ordinary stream delta, but is more in the nature of a narrow subaqueous platform merging with the beach near the shoreline and dropping off abruptly to deeper water at its seaward margin. When cusps have not formed, the margin of this platform is relatively straight; but after cusps have developed, the greatest amount of water returns down the slope from the intercusp spaces, building the subaqueous platform seaward more rapidly than does the smaller amount of water returning from around the apices of the cusps. In this way the margin of the platform becomes scalloped, each intercusp space having a scallop or miniature delta to correspond with it. It is evident that the scalloping of the platform presents no difficulty if the origin of the cusps is understood.

RELATION OF BEACH CUSPS TO OTHER FACTORS OF SHORE ACTIVITY

In collecting data concerning beach cusps some attention has been given to several other factors of shore activity, in view of the possibility that they might exert some influence on cusp formation. Several of these factors are briefly treated below.

It was thought at first that the angle of beach slope might exert an important control over the spacing of the cusps, inasmuch as the slope affects both the volume and velocity of the water advancing and retreating over the zone of wave attack. It soon became apparent, however, that if the inclination of the beach does influence the spacing, the effect is largely masked by the far more important factor of wave size. I still think it probable that the slope of the beach plays a small part in the spacing of cusps, but have not sufficient data on this point to demonstrate the truth of the theory.

The direction of the wind seems to have little effect on the formation of cusps. They have been observed in process of formation during onshore, offshore, and longshore winds, both gently and fairly strong. Under ordinary conditions the only result noticed was a more or less marked cliffing on one side of the cusps when the wind produced small waves at an angle oblique to the beach. The cusps thus cliffed may have been partially developed before the oblique waves began their work. If the wind is strong enough and from such a direction as to combine with the breakers in producing a very irregular wave attack, the formation of cusps is probably interfered with, since numerous observations tend to show that a fairly regular advance and retreat of the water is essential to their development.

Beach cusps are formed at all stages of the tide. It is probable that the greatly elongated type is produced when the waves remain of approximately the same size during a falling tide, but the development of this type has not been observed throughout the entire process.

The direction of wave advance has been carefully noted wherever cusps were being formed. On the basis of numerous observations on all kinds of beaches and of extended experimentation, it may be confidently stated that the best conditions for cusp formation exist when a single series of waves advances parallel with the beach. It is possible that cusps may be produced by waves striking the shore at a markedly oblique angle, but no satisfactory evidence that such is the case has been secured. On the other hand, the progressive destruction of cusps by oblique waves has been repeatedly observed. Such partially destroyed forms are shown in the lower left-hand corner of figure 3. I am inclined to think that the asymmetrical "cusplets" reported by Wilson (122) were formerly symmetrical beach cusps of the ordinary type, which were later cliffed by the oblique waves shown in a photograph reproduced in his paper. Intersecting waves of the type hypotheticated by Branner have been seen in a number of cases, but no cusps have been observed to develop under the action of such waves.

The periodicity of the waves does not appear to be a significant factor in beach cusp formation. Varying the period with artificial waves produces no apparent effect on the cusps.

Jefferson says (1903, 124): "The cusps seem related to a longshore current, their precise cause not being evident;" but he does not indicate in what manner the cusps seemed related to the current. In most of our observations no evidence of a longshore movement of the water was found. In the few cases where a distinct drift or current in one direction was apparent there seemed to be no relation between the current

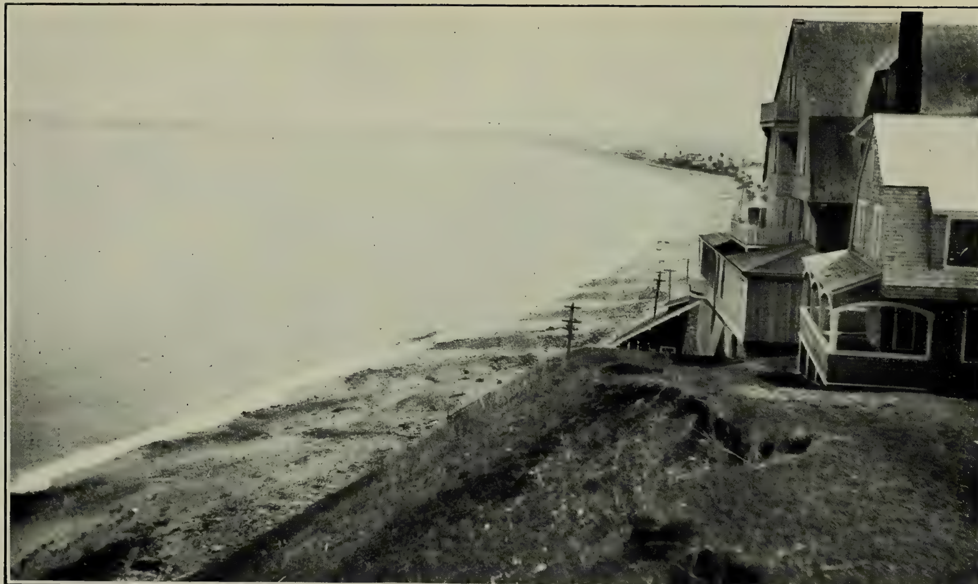

FIGURE 1.—COBBLESTONE CUSPS ON NANTASKET BEACH, NEAR BOSTON

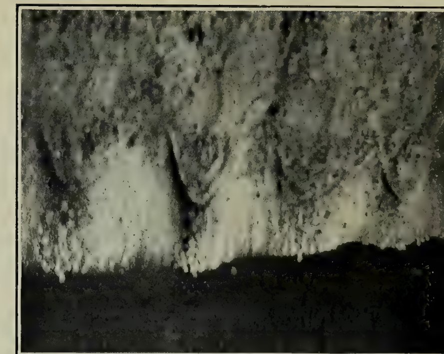

FIGURE 2.—ARTIFICIAL CUSPS

BEACH CUSPS

and the cusps. Beach cusps are clearly the product of on- and off-shore movements of the water.

ARTIFICIAL BEACH CUSPS

From the observation of natural beach cusps in process of formation the conclusion was reached that cusps could be formed by a single series of waves advancing parallel with the shore. In order to test the validity of this conclusion the artificial production of cusps was attempted. A sand beach was constructed along one side of a tank 5 feet square and the water in the tank raised until it rested against the beach slope. To make that slope as smooth and gentle as possible, large waves were washed over the beach until it appeared to the eye as a perfectly uniform, gentle slope of sand. On the opposite side of the tank from the beach was arranged the wave-producing apparatus. This consisted at first of a board which was tipped up and down by hand; later of two boards hinged together, one of which was made stationary on the floor of the tank, while the other could be raised and lowered by a long handle connecting with its free edge. With this simple apparatus it was possible to propel on the beach a series of parallel, straight waves, varying in size and periodicity as the experimenter desired. It was found that beach cusps resembling closely those in nature could be artificially produced (plate 42, figure 2). The characteristics of those artificial cusps have been discussed above.

Theories of Origin

With the characteristics and variations of beach cusps in mind, we may examine the theories which have been proposed to account for their origin.

SHALER'S THEORY

According to Professor Shaler, "the inner edge of the swash line . . . has a very indented front, due to the fact that it is shaped by a criss-cross action of many different waves." The projecting tongues of water push back the pebbles, leaving indentations or bays, which are then enlarged under the continued wave attack during the rising tide. It should be noted, however, that the indentations of the inner edge of the swash line on a smooth beach are extremely irregular, and vary in position with every wave advance until the development of cusps and intercusp depressions affords more definite guidance. That a single advance of the irregular inner edge of the "swash" could develop bays which would thereafter control the action of the waves seems doubtful. The inner edge of the swash is thin as well as irregular and variable, and under these conditions must be very ineffective in developing intercusp spaces or "bays." Nor does the theory as stated by its author explain the regularity in spacing of the cusps nor their respacing consequent upon a change in size of waves. It would seem that Professor Shaler's theory does not go far enough adequately to explain the observed phenomena.

CORNISH'S THEORY

In the account of "ridges and furrows" (cusps and intercusp spaces) given by Cornish, it is stated that the water washes depressions at selected places because neither the force of the water nor the resistance of the beach material to erosion are absolutely uniform. The regular spacing of the cusps is not explained, nor does the author appear to have recognized this character of their distribution. Neither does he recognize the fact that gentle waves build cusps. The erosion which produces the "furrowing" is related by him to a change from small to large waves only. But we have seen that cusps form under the reverse conditions as well. It thus appears that Cornish points out certain causes of the unequal erosion of beaches, but does not throw much light upon the origin of the cusps.

JEFFERSON'S THEORY

The seaweed barrier theory of Jefferson, advanced to account for the occurrence of cusps on a beach where there happened to be considerable accumulations of seaweed at the time, breaks down under the test of a broader application. There are also serious objections to the theory aside from the fact that cusps are abundantly developed on beaches free from seaweed and other similar material. Even if we admit that a strip of seaweed might form an effective dam behind which considerable masses of water would be imprisoned, we must regard it as in the highest degree improbable that this water would break through the seaweed barrier at a large number of rather evenly and often closely spaced intervals. The degree of regularity in beach cusp spacing is wholly incompatible with the seaweed barrier theory.

On the other hand, it should be remembered that after the cusps have once formed, a seaweed barrier, as well as a barrier of sand or gravel, may be breached by the waves where their water is concentrated for the attack in the intercusp spaces. Thus an observer might find breaches in the barrier corresponding with the intercusp spaces. As shown more fully on a preceding page, both theoretical considerations and the field evidence support the view that the breaching is effected by direct wave attack, and not by the escape of water imprisoned behind the barrier. There is good ground for the belief that the breaching of the seaweed barrier on the Lynn Beach was the effect instead of the cause of cusp formation.

In Jefferson's more recent accounts the question of origin is very briefly referred to; but from such reference it appears that the author considers a barrier of sand or gravel capable of playing the same rôle in cusp formation as a seaweed barrier. It is further implied that other cusps must have had a different but unknown origin. The objections urged against the seaweed barrier theory apply, in the main, with equal force against the sand or gravel barrier theory. It is true that ridges of sand and gravel are more frequent on beaches than barriers of seaweed; but the evidence is conclusive that cusps are formed when such ridges are absent, and that even when present such ridges are breached from the seaward side by direct wave attack, and not from the landward side by impounded waters.

On both natural and artificial beaches more or less distinct ridges are sometimes broken through before any distinct cusps have been formed. This led me to entertain the hypothesis that direct wave attack on a fairly uniform ridge would develop breaches in the ridge at intervals proportional to the size of the waves. It seems probable, however, that faint undulations in the beach, on the seaward side of the ridge, may help to determine the points of breaking, just as the more evident cusps and intercusp spaces do in other cases, and that the breached ridges are therefore but one phase, and not an essential one, of the process of cusp formation, as explained on a later page.

BRANNER'S THEORY

Branner's theory, while very suggestive, seems to present insuperable obstacles, as will be apparent on the inspection of the accompanying diagrams (figures 1 and 2). The hypothetical wave lines are evenly spaced, and the wave length in both sets is the same. This is a condition which probably never obtains in nature, and yet such an improbable condition is an essential element of the theory. If the two sets of waves are given different wave lengths, or if one set of waves has a velocity differing from that of the other, or if either set of waves is irregularly spaced, then the points of wave interference will not reach the beach at the same place twice in succession. If we endeavor to approximate natural conditions by introducing any one of the three types of irregularities mentioned (and probably all three exist in every case of intersecting waves), we must correct the diagrams by making the dotted lines meet the shoreline at every conceivable point. This done, the supposed reason for cusp formation disappears.

It has been shown on preceding pages that the physical conditions necessary for cusp formation exist in parallel waves. One might accordingly surmise that in intersecting waves the necessary equilibrium would be destroyed and the formation of cusps rendered more difficult, or even impossible. I believe this to be the case. In 1907, while camping near Huletts Landing, opportunity was afforded to make numerous observations during a period of six weeks, on a portion of the lake shore where intersecting waves were usually developed by a sand and gravel bar offshore. At no time were cusps observed on the portion of the beach where intersecting waves arrived, although they were frequently found on adjacent portions. These observations led to the belief that intersecting waves tend to prevent rather than to cause the formation of beach cusps.

WILSON'S THEORY

Inasmuch as the "cusplets" described by Wilson appear to be true beach cusps of somewhat unusual form, it is proper to consider the hypothesis offered to account for their origin. According to this author, evenly spaced waves striking a straight shoreline at an oblique angle will give evenly spaced points of wave breaking at which cusps will develop. Because at any given instant a series of oblique waves will be breaking at a number of different points along a beach, the author assumes that the points of simultaneous wave-breaking will be nodal points where material will tend to accumulate. It would appear that no account is taken of the fact that every oblique wave of the series breaks not only at the point observed during a given instant, but also at all the other points up and down the beach, so long as the wave exists. The point of breaking of an oblique wave sweeps along the shore until the end of the wave itself is reached. In a series of waves parallel to each other, but oblique to the shoreline, each wave in turn breaks continuously from one end of the beach to the other. Under these conditions no nodal points can develop, and the fact that the waves are a given distance apart, and that at any given instant their points of contact with the shore are evenly spaced, is immaterial so far as the distribution of force of wave attack is concerned.

In addition to the theoretical objections to Wilson's theory must be added the observed fact that oblique waves appear to be much less favorable to cusp formation than are waves parallel to the shoreline. Oblique waves have been observed in the process of cliffing the sides of cusps exposed to their attack, and the remains of the cusps then have the asymmetrical form described by this author.

ADDITIONAL THEORIES

In attempting to explain the formation of beach cusps I have tested and rejected several working hypotheses in addition to those mentioned above. For example, there was considered the possibility that the waves breaking parallel with the shore had superposed obliquely upon them smaller waves, and that the portions of the main waves thus increased in height excavated the intercusp spaces. One bit of evidence which appeared to harmonize with this theory was reported by Mr. Read, who noted that on Virginia Beach the incoming waves showed the first tendency to break at regularly spaced intervals which corresponded with the intervals between cusps. The hypothesis was rejected because the cause was irregular, while the effect was regular, because of an almost complete lack of direct evidence pointing to a relation between superposed waves and cups, and because the experiments seemed to point conclusively to some other origin.

Another hypothesis was based on the assumption that an extended sheet of water descending an inclined plane may not move with the same velocity throughout, but may tend to develop lines of swifter flow, or currents, at certain intervals. I was tempted to make this assumption because of the fact that water descending a flat-bottomed inclined trough, or conduit, does not flow uniformly, but is successively retarded in such a manner as to produce a succession of waves. Admirable illustrations of this phenomenon have recently been published by Vaughan Cornish in a paper on "Progressive Waves in Rivers" (1907). It occurred to me that if a broader sheet of fluid were retarded by friction while descending an inclined plane, the resistance might be overcome first, or more rapidly, at certain points, and that the slightly increased rate of advance at these points would disturb the equilibrium in such manner as to create zones or currents of accelerated flow wherever these slight initial advantages had been gained. If the sheet of water were shallow, there would be a tendency for the currents to be smaller and more closely spaced than if the sheet of water were of greater depth. This hypothesis was especially tempting, inasmuch as granting the basal assumption all the phenomena of beach cusps find a ready explanation. Small waves advancing and retreating on the beach would give small currents closely spaced, which would in turn scour small intercusp spaces leaving closely spaced cusps. Any change in the size of waves resulting in a change in the size and spacing of the currents would necessitate a respacing of the cusps. The hypothesis does not lack support so far as the phenomena of beach cusps are concerned, but it is based on an assumption which does lack support. I have questioned a number of engineers and physicists in regard to the matter, but could learn nothing favorable to the assumption.

The hypothesis which best accords with all of the available evidence may now be set forth. Concisely stated, it is that selective erosion by the swash develops from initial irregular depressions in the beach shallow troughs of approximately uniform breadth, whose ultimate size is proportional to the size of the waves, and determines the relatively uniform spacing of the cusps which develop on the intertrough elevations. This theory differs essentially from those proposed by Branner and Wilson in that neither intersecting nor oblique waves are appealed to and the spacing of the waves is disregarded; from those proposed by Jefferson and Cornish in that the cusps are not regarded as mere erosion remnants of a once continuous ridge, while uniformity of spacing depending on wave size is considered of vital importance; from the theory proposed by Shaler in that no importance is attached to the irregular front of the swash, the ability of the thin edge of the swash to develop the intercusp bays is not admitted, while the size of the wave is correlated with the width of intercusp spaces. Other points of difference will appear in the explanation which follows.

Every beach contains numerous inequalities which tend to prevent a uniform flow of water up and down the beach during wave action. These inequalities have a variety of causes. Surface run-off after rains may develop channels on the beach; the water draining out of the sand at the upper part of the beach after high tides or after high waves may produce the same result. Pebbles lying on a sandy beach interfere with the "swash" of water up and down the beach, and cause some channeling. The waves are never even crested, and may be very irregular if oblique waves are superposed on them; the irregularity of the "swash line," mentioned by Shaler, may initiate irregularities on the beach. Remnants of old beach cusps, not wholly obliterated, form another source of irregularity; and still other sources might be mentioned.

The continual swashing of the water up and down the beach tends to enlarge the irregular depressions over which the water passes. Larger channels are better adapted to the movements of the large volumes of wave-supplied water. It is inevitable that in the enlarging of some depressions others will be obliterated, just as in the case of growing drainage basins many small basins disappear as independent features, while the few increase in size. Those depressions on the beach which develop to larger proportions will be the ones which have some initial accidental advantage, and which increase that advantage as they grow; just as the accidentally favored drainage basins increase in size and advantage at the expense of those which began the contest with but a slightly less favorable chance. The tendency of wave action will be to develop from initial irregularities a smaller number of broad and shallow depressions on that portion of the beach traversed by the swash. The depressions will be broad, because they are thus better adapted to the movements of large volumes of water, and shallow, because the elevations between the depressions are also buried under the advancing and retreating waters and are kept worn down to a moderate height. Only near the upper zone of wave action, where the water invades the depressions but does not rise high enough to override the intervening elevations, are the depressions continually scoured deeper and the unworn elevations left as pronounced ridges. Out toward the seaward margin of the submarine terrace, deposition rather than erosion prevails, and the delta scallops may rise higher than the seaward extension of the elevations which exist farther up the beach.

There is a limit to the width to which the depressions, or shallow "channels," if we may so call them, can develop. Inasmuch as the enlargement of some necessitates the obliteration of others, enlargement will continue only so long as the impulse toward growth imposed on the more favored channels is sufficient to overcome the tendency of their neighbors to enlarge. Equilibrium will be established when adjacent channels are of approximately the same size, and at the same time of a size appropriate to the volumes of water traversing them. If the waves are low and the volumes of water consequently small, equilibrium will be reached while the channels are yet small. But if the waves are high and the volumes of water large, a perfect adjustment will not be reached until the channels have attained considerable size.

The remainder of the process is easily understood. With the water advancing repeatedly up a beach which is faintly but systematically channeled, as above indicated, there will be a constant tendency to push gravel and other debris farther up the slope in the depressed areas than in the intervening areas. Near the upper limit of wave action the depressed areas alone are invaded by water and are scoured deeper as the gravels are pushed back and the finer material dragged down to form the delta scallops. The intervening areas are fashioned into beach cusps, whose sharpened points divide the waters of the advancing waves and concentrate the attack toward the heads of the depressions. The coarse material is constantly pushed into the cusp areas, the channels swept relatively clean. With a rising tide, both channels and cusps are pushed progressively up the beach; with a falling tide, some of the gravels may be dragged downward to give much elongated cusps.

There are a number of considerations which appear to support the foregoing theory of beach cusp formation. The theory accounts for the degree of regularity observed in the spacing of beach cusps, since the spacing is dependent on the development of channels which do not reach equilibrium until of approximately uniform size. At the same time the considerable degree of irregularity in spacing occasionally observed is not incompatible with the theory, since the degree of regularity in spacing depends on the progress which has been made toward the establishment of perfect equilibrium. The occurrence of imperfect and compound cusps is readily explained as the product of wave action in channels not yet eroded to the standard size, as when two unusually small channels have not yet been fashioned into a single large one, and consequently give a compound cusp near their upper limits. We should expect, on the basis of this interpretation, that irregular and compound cusps should be most characteristic of the early stages of development, and the experiments with artificial cusps prove most conclusively that this is the case. One of the commonest occurrences in the experiments is the gradual moulding of irregular and compound cusps into simple cusps regularly spaced.

The respacing of cusps with a change in size of waves may be thus explained: A given set is formed and driven up the beach, and then left by the falling tide. The size of waves changes, and new channels appropriate to them are formed. New cusps result, and as the tide rises these are in turn pushed up the beach. If the new cusps do not coincide in position with the older ones, when the latter are reached their ends will be eroded by the waters converging on them from between the new ones. Repetitions of this process, with waves of decreasing size, will give several sets of partially preserved cusps, each set more closely spaced than the set above it. On the other hand, if a big storm drives in unusually high waves, big channels will be formed, older sets of cusps will be quickly swept out of existence, and a single set of large, widely spaced cusps will be developed.

In the laboratory experiments difficulty was often experienced in getting the cusps started. The artificial beach was very smooth, of fairly uniform sand grains. It appeared that the difficulty was due to the regularity of the beach, on account of which the initiation of channels was delayed. In order to facilitate the process a series of closely spaced creases down the beach was made, after which the cusps began to form more rapidly. As already shown, the artificial creases did not control the number or position of the cusps and their intervening spaces, but the importance of initial depressions in the cusp-making process seemed clearly indicated.

On Westquage Beach, Rhode Island, the writer has watched a series of parallel "creases," or rill lines, without any associated cusps, develop into channels or intercusp spaces with fairly good associated sand cusps. Such observations are relatively rare, however, probably because the initial irregularities are often indistinct undulations in the beach surface or are soon transformed into such undulations, and because the successive changes in the form of broad, shallow channels on a gravel or sand and gravel beach are difficult to trace. The "ribbed" structure occasionally reported by observers looking for cusps probably represents an early stage of cusp formation.

The tendency of intersecting or crisscross waves would be continually to shift the sands first in one direction and then in another obliquely over the beach, and thus to prevent the formation of systematic channels. This would account for the observed failure of such waves to form beach cusps, although they might attack cusps previously formed, or leave a beach with irregularities which might affect the formation of later cusps. In a similar way, to a less extent, a single series of oblique waves would not seem favorable to cusp formation, because of the lateral element in the movement of the water, which would continually tend to wash the interchannel elevations into the channels, and so to fill them up.

It is not necessary to review all the details of beach cusp characteristics in connection with the theory set forth above. It is sufficient to state that the writer has found no feature of beach cusps which is incompatible with the theory, while the conditions of wave action hypotheticated appear to rest on a reasonable basis.

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CRITERIA FOR THE RECOGNITION OF THE VARIOUS TYPES OF SAND GRAINS[1]

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(Presented before the Society December 29, 1909)

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The Thesis Stated

From the physical characteristics and composition of sand grains is it possible to decipher their origin and geological history? This is the question which the writer set himself the task of answering while endeavoring, conjointly with Prof. A. W. Grabau, to determine the origin of a certain Silurian sandrock—the Sylvania, known in outcrop and borings about the western end of Lake Erie. It may be answered that *typical* assemblages of the various varieties of sand grains do reveal their own geological history, and that confirmation of this history may be obtained often from a detailed study of the beds in which these grains occur. Concerning the origin of the material from which the grains were carved one may speak less confidently, but with all the obtainable data at hand it seems possible that here, too, a definite answer may be found for each particular deposit. In his presidential address before the Geological

[1] Published by permission of the State Geologist of Michigan, Prof. R. C. Allen. Manuscript received by the Secretary of the Society February 9, 1910.

Society of London, in 1880, Sorby called attention to the necessity of distinguishing between the age of the grains themselves and the age of the deposit in which they may be found.[2] It should be added, further, that we must distinguish between the geological history of these grains and that of the deposit in which they have last found lodgment. It is conceivable that sand grains may pass through one or several cycles of developmental history, from the mechanically crushed glacial sand to the highly finished æolian product; from the sharp, angular, freshly appearing granule to the ellipsoidal, or spherical, frosted and pitted type of granule. The condition and nature of the grains themselves may not accord with that of the deposit in which they occur, æolian sands being blown to sea or shore deposits seized by the winds and made into dunes. In this paper there is no attempt to review the literature relating to sand and its production, but simply to cull out that portion of it bearing on the above stated problem.

The writer has gotten together from various sources as many samples of sand as possible, and from first hand studies on the same has endeavored to confirm, as far as possible, the observations of others and arrive at an independent judgment concerning the distinguishing characteristics of the various types and subtypes. The study has been far from exhaustive and has suggested to the writer, and may do so to others, many varieties of sand for which search may be made. The camera has been brought into requisition upon typical mounts of these sands, and the views thus obtained reproduced here in half-tone, thus revealing much that can not well be expressed in language. No photographic plate however, can receive and record fully the great variety of impressions that the eye receives directly from such material.

Classification of Sand Grains

The classification adopted is based on the various agencies responsible for the production of the sand, and to the extent that these agencies suggest to the geologist at once the mode of production the classification is genetic. It was soon found that a classification based on the general form of the granules, such as that proposed by Sorby in 1879,[3] and copied somewhat generally, would be found unsatisfactory if made to cover all types of sand. Sand as different as glacial, residual and volcanic in method of production, composition, and condition would be

[2] On the structure and origin of non-calcareous stratified rocks. Quarterly Journal of the Geological Society of London, vol. xxxvi, 1880, Proceedings, p. 58.

[3] Quarterly Journal of the Geological Society of London, vol. xxxvi, 1880, p. 58.

thrown together under one heading. Similarly aqueous, æolian, oölitic and much volcanic sand would have to be grouped together because of general similarity in the shape of the granules. Chemical composition is almost as unsatisfactory as a basis of sand classification for similar reasons. In the classification adopted it was found that the main varieties of sand commonly encountered may be distributed under seven distinct *types;* but since the sand-producing agencies are in operation more or less continuously, these types may be still further acted on by one or more of the other agencies, and intermediate *subtypes* be produced. To distinguish these subtypes a system of compound terms is proposed, in which the last term designates the type form and the first term indicates the agency by which the type has begun to be modified. In this way a large number of intermediate varieties of sand, many of them of much geological importance, may be designated very simply as soon as their mode of production can be determined. To illustrate: An *aqueo-residual* sand is one in which the granules have been produced by the various residual agencies and have been subsequently more or less modified by water action. A *residuo-aqueous* sand, on the other hand, is to be understood as one in which water-rounded granules have been subjected to the agencies of weathering, and give more or less evidence of such action. Through these subtypes the aqueous and residual types of sand are connected, as they are found to be in nature, to the extent that the secondary agency has operated on the original type. If the water action is complete enough to obliterate all traces of the residual action, or if the residual agencies have shattered and destroyed the aqueous sand beyond recognition, then the subtype passes into one of the other types. This same system of classification will be found to apply to *pebbles* on one hand and the variously formed types of *dust* on the other, thus bringing out the intimate relation between sand and all such clastic material.[4] The distinction between these three classes of materials is, of course, entirely arbitrary, and would be made differently by different investigators. In describing a residual sand from Medford, Massachusetts, Merrill[5] makes the following distinctions: Gravel, above 2 millimeters; fine gravel, 2 to 1 millimeter; coarse sand, 1 to .5 millimeter;

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[4] As presented in this paper the classification is not absolutely complete, several geologically unimportant varieties of sand not being included, in order to secure the desired simplicity. In the manufacture of talus, in avalanches, rock slides, rock and mud flows and earth movements along joint-planes, sand is produced along with coarser and finer material, of a nature quite similar to that due to glacial action. Meteoritic matter of sand-like texture may also reach the earth and be recognized by form and composition. It seems quite possible that rounded sand grains might originate by concretionary action of the clay-ironstone variety and be segregated by some agency.

[5] U. S. Geological Survey, Bulletin No. 150, 1898, p. 380.

medium sand, .50 to .25 millimeter; fine sand, .25 to .10 millimeter; very fine sand, .10 to .05 millimeter; silt, .05 to .01 millimeter; fine silt, .010 to .005 millimeter; clay, .005 to .0001 millimeter.

Glacial Sand Type

When freshly assorted and deposited by the glacial drainage streams the sand resulting from the mechanical crushing of crystalline rocks by glaciers is sharp, angular, fresh, and bright under the microscope, showing but little evidence of weathering or of wear (see figure 1, plate 43). The quartz grains are strongly vitreous in a good light, show the characteristic conchoidal fracture, have sharp edges and keen points. The cleavable minerals exhibit fresh looking cleavage surfaces, seams, and edges, and give but traces of internal decomposition due to incipient weathering. There is generally much variety of mineral represented, depending, of course, on the nature and composition of the rocks serving as the parent beds. The sand collected from the banks of glacial streams or from their deserted beds is generally poorly assorted, leading to considerable variation in the size of the constituent particles. Owing to their size and the inability of the glacier to hold them firmly, faceted and glaciated sand grains would scarcely be expected; still an occasional larger grain may be found showing such facets and scratches, very suggestive of those carried by boulders from the till.[6] An occasional well rounded granule may be met with, as seen in figure 1, plate 43, which may belong to another phase of granular development, water-borne or wind-blown, or the form may have been originally present in the parent bed. Sand washed from the pleistocene till deposits exhibits the same general characteristics above enumerated, but with a considerably larger proportion of roughly or completely rounded granules (see figure 2, plate 43). These give evidence of abrasion and wear after their formation by the glacier, the sharp corners and edges showing some rounding and yielding a subangular type of granule. Weathered grains are more numerous than in the sand from modern glaciers, and they exhibit signs of external corrosion rather more pronounced in the earlier than the later till deposits.[7] Washed from these till beds, assorted and still further rounded by water action, we have the source, undoubtedly, of much of the sand of glaciated and adjacent regions. Such sand subjected to

[6] Note the remark of Mackie in Edinburgh Geological Society, vol. vii, 1896, p. 151.

[7] Sorby: On the structure and origin of non-calcareous stratified rocks. Proceedings of the Geological Society of London, vol. xxxvi, 1880, p. 59.

Evans: Felspars in sedimentary rocks as indices of climate. Transactions of the Edinburgh Geological Society, vol. vii, 1898, pp. 445 and 459.

but a slight amount of water erosion is obviously not to be distinguished from that found in the till, so far as the granules themselves are concerned. Embedded in the till there occur often lenticular, stratified deposits of such sand, and in the basal layers of the beaches of glacial lakes, which may or may not have been subjected to much aqueous action. Such sand, which shows by the modification of the granules themselves the action of water, may be conveniently referred to as of the aqueo-glacial subtype.

Volcanic Sand Type

So far as the general form of the granules is concerned, the sand resulting from the action of volcanoes on solid lavas may resemble on one hand that obtained from glacial action. The grains are often very irregular and sharply angular, and give no evidence of erosion about the corners and edges. The assorting is due to gravity acting on the ejected materials while buoyed up by the atmosphere, and may be more or less complete, always more so than in glacial deposits and generally less than that due to water action. The stratification resulting is quite regular and horizontal, and free from any cross-bedding or rippling. In the case of the vitreous materials the sand fragments in their form, luster, and method of breaking may much resemble freshly pulverized glass, seen especially as the sand approaches dust in its texture (see figure 3, plate 43). The coarser particles give evidence of rounding due to mutual abrasion while suspended in the air, or, in the case of derivation from molten or plastic lava, from having been thus molded during their aerial flight, and may pass into lapilli (see figure 4, plate 43). Well defined outlines of isolated crystals may often be observed, the corners and edges giving more or less evidence of erosion while in the solid condition. The granules derived from volcanic sand generally contain much amorphous material, or show only incipient crystallization, exhibit flowage structure and are more or less vesicular (see figure 3, plate 43), by which they may be readily distinguished from ordinary glacial sand.[8] In the case of a glacier acting on a series of lava beds there may be produced a type of sand very similar, possibly nearly identical, with volcanic sand and to be distinguished from it chiefly by the nature of the deposit in which it occurs. When separated from their parent beds by slight water action the volcanic sand may be expected to show more rounding

[8] A discussion of how volcanic sand may be produced and a description of a sample from the Snag Lake cinder cone, California, is given by Diller in Bulletin No. 150 of the U. S. Geological Survey, 1898, p. 245. See also The eruption of Krakatoa, Report of the Royal Society of London, 1888, p. 38. Russell: Volcanoes of North America, 1897, p. 75.

and more detached crystal fragments than the glacio-volcanic subtype and a complete absence of striated facets. Sand washed from the mud flow that overwhelmed Herculaneum shows considerable rounding, which might plausibly be ascribed to the mutual abrasion of particles during the flow of a few kilometers. It seems to sustain about the same relation to ordinary volcanic sand that sand washed from the till sustains to freshly formed glacial material. An examination of the sand, however, which fell upon Pompeii directly from the atmosphere during the same eruption shows about the same degree of rounding, and suggests that in both cases the cause was the same.

Residual Sand Type

Sand of this class results from the complicated set of agencies comprehended under the general term of "weathering," acting on rocks of the plutonic or volcanic type. Through unequal expansion and contraction due to temperature changes, expansion due to ice formation in the crevices, or hydration of constituent minerals in the body of the rock, the surface of the bed is disrupted and disintegrates into a gravelly sand. This action is hastened by various chemical changes and solution, and if long enough continued results in the formation of a rusted soil. The conditions under which such changes occur have been fully discussed[9]; our chief interest here is in the resultant type of sand grain. From the method of formation residual sand must be poorly assorted, what assortment there is being due to the removal near the surface of the finer material by wind or rain wash and the fact that the texture becomes gradually coarser as one descends toward the parent bed. This means that the residual deposit is better assorted than the glacial and more poorly than the volcanic. Under the microscope the granules appear decidedly angular, with no evidence of secondary rounding (see figures 5 and 6, plate 43). Isolated crystals and crystal fragments are in evidence, indicating a tendency of the constituent minerals to drop apart,

[9] Hunt: The decay of rocks geologically considered. American Journal of Science, 3d ser., vol. xxvi, 1883, p. 190.

Chamberlin and Salisbury: The driftless area of the upper Mississippi Valley. Sixth Annual Report of the U. S. Geological Survey, 1885, p. 239.

Russell: Subaërial decay of rocks. Bulletin No. 52, U. S. Geological Survey. In this bulletin will be found a full list of references up to the date of its publication in 1889. See also

Shaler: The origin and nature of soils. Twelfth Annual Report of the U. S. Geological Survey, 1891, p. 219.

Merrill: Rocks, rock-weathering, and soils, 1897, parts iii and v, and Bulletin No. 150, U. S. Geological Survey, 1898, p. 376. The most comprehensive and most recent discussion of the various residual processes will be found in Van Hise's "Treatise on metamorphism," Monograph XLVII, U. S. Geological Survey, 1904, p. 409.

somewhat as seen in volcanic, but not noticeable in glacial sand (see center of figure 5, plate 43). The chief characteristic by which residual sand is to be distinguished from the preceding types is by the pronounced weathering of all the minerals capable of such change. Many of these minerals become opaque, clouded, or deepened to yellow, deep green, or brown, strongly suggesting age and decay. Goodchild has pointed out marked differences in the weathering of eruptive rocks and limestones, depending on the amount of humidity[10] present. Under arid conditions the disintegration is very largely mechanical, resulting in the splintering of the cleavable minerals into fresh, angular fragments, while under moist conditions there is more or less chemical decomposition, especially detectable in the feldspars. In the same volume (page 444) Mackie reaches the same conclusions in his paper, "Felspars in sedimentary rocks as indices of climate," read in 1898.[11] The resistant quartz crystal fragments often are coated with iron oxide and the microscopic mount gives evidence of age not seen in any other type of sand. When originally present in the parent rock the softer mica still remains much in evidence, showing its ability to resist the processes of decay quite as well as some of the harder minerals. Subjected to mechanical abrasion, this would be the first of the common rock-forming minerals to disappear.

When a bed of till is exposed for a long enough time to the various agencies of weathering, the same ingredients take on the above characteristics, and there results a subtype of sand showing a combination of characters which may conveniently be referred to as residuo-glacial. The pre-Kansan (Nebraskan), Yarmouth, Sangamon, and Peorian weathered zones of the various till sheets described by Leverett,[12] give evidence that the pebbles, and presumably the sand grains, but probably to a less extent are passing into this condition. Removed from its associations in the parent bed by slight water action, the typical residual sand is distinguished from the residuo-glacial variety by the scarcity in the latter of the softer minerals and detached crystals and the relative abundance of rounded granules. The typical glacial sand is to be distinguished from the residuo-glacial variety by the evidence in the latter

[10] Desert conditions in Britain. Transactions of the Edinburgh Geological Society, vol. vii, 1896, p. 205.

[11] See also Merrill in Bulletin of the Geological Society of America, vol. 7, 1896, p. 359.

Barrell: Studies for students. Journal of Geology, vol. xvi, 1908, pp. 171, 176, and following.

[12] Proceedings of the Iowa Academy of Sciences, vol. v, 1898, pp. 8 and 18. Journal of Geology, vol. vi, 1898, pp. 171, 238, and 244. Monograph XLI, U. S. Geological Survey, 1902, pp. 292 and 302. American Journal of Science, vol. xxvii, 1909, p. 349. See also paper by Shaler in Twelfth Annual Report of the U. S. Geological Survey, 1891, p. 236.

of extreme weathering, and the same criterion may be used to distinguish volcanic from what may be termed residuo-volcanic sand. The passage of such volcanic sand into residuo-volcanic material has been described by Shaler in his paper previously cited, "Origin and nature of soils" (page 239). In the case of a residual sand subjected to but slight aqueous action of stream or wave, not enough to materially change the form of granule nor completely remove the coating of iron oxide, we have a subtype of sand which may be termed conveniently aqueo-residual and which may be found to comprise the body of numerous beds of sandstone and arkose. This explanation is assigned to the formation of the Newark system (Jura-Trias) of the Appalachian region by Russell, in the bulletin previously referred to (No. 52, page 44-46), and its color accounted for. This author believed the red color to have resulted directly from the weathering under warm, moist conditions (pages 27 and 30). Barrell has shown that there is reason for thinking that with sufficient time only a moderate heat is required, and that the red color may be developed in subaërial deposits under conditions of aridity.[13]

Aqueous Sand Types

For convenience of study, sands which owe their characteristics to the action of moving water may be divided into river and beach sands, but under the microscope they appear essentially alike and are not to be distinguished from one another. In the case of minerals of the same or very similar specific gravity, quite complete assorting may often be noted. The most complete effect of this nature may be obtained, as recently pointed out by Sorby,[14] to a bottom current in comparatively shallow water. To use his own language, "more or less perfect similarity in the size of the grains usually indicates a sorting of the material by a current at the very bottom of comparatively shallow water; whereas great irregularity in the size indicates that the material was deposited from much deeper water, in which there was little current at the bottom, though a good deal of current higher up."

Under such favorable conditions the assorting power of water exceeds that of any of the previously discussed agencies, being approached only by the volcanic and exceeded only by the æolian. Similarity in size presupposes that the granules possess approximately the same structure and

[13] Climate and terrestrial deposits. Studies for students. Journal of Geology, vol. xvi, 1908, pp. 285 to 287.

[14] Sorby: On the application of quantitative methods to the study of the structure and history of rocks. Quarterly Journal of the Geological Society of London, vol. lxiv, 1908, p. 185.

specific gravity, while if these properties vary considerably there would occur a corresponding variation in the relative sizes of the granules deposited in the same bed. The experiments of Sorby, reported in the above cited paper, indicated that a current of about 6 inches per second is sufficient to slowly drift along granules of common sand having a diameter of about a hundredth of an inch. No rippling of the sand was produced until the velocity of the current was somewhat greater (page 180). The "angle of rest," in water, of sand averaging about .05 inch (ranging from .03 to .07 inch), he found to be about 41 degrees when simply coming to rest, but about 49 degrees before giving way after having been at rest. For smaller sized granules the angles were less, being 34 and 36 degrees for grains averaging .01 inch and 30 and 33 degrees for sand averaging about .003 inch in diameter (page 174). The author describes (pages 186-188) what he terms "drift-bedding" as resulting when sand drifted by a current reaches relatively deeper water, by which the velocity is checked and the sand deposited at the angle of rest in a bed, the thickness of which corresponds to the increased depth. When deposited by currents of water the angle of rest is considerably reduced. As a result of the steep angles of rest, sand deposited under rapidly shifting currents may show very marked cross-bedding. In the case of all classes of aqueous deposits there is always the possibility of the introduction of marine or fresh water forms of animal or plant remains. No especial significance, however, can be attached to their absence, since a bed of rapidly accumulating or shifting sand is unfavorable for life and the permeability of a sand deposit favors the decay and removal of organic forms. In the case of granules practically insoluble in ordinary water, the shaping of the same is due mainly to their mutual abrasion while in motion. Based on a study of the modern and ancient sands of Great Britain, Mackie in 1897 developed a formula expressing the capacity of sand grains to become rounded in water, the factors involved being the size, specific gravity, hardness, and distance traveled.[15] It was found that the larger grains showed the most evidence of rounding; that where the grains were of about equal size the heavier were the more rounded; that where size and specific gravity were about the same the softer showed the more rounding. In those cases in which the source of the sand could be determined it was shown that those sands which had traveled the farthest were the most rounded. Assuming the size, shape, and distance

[15] Mackie: On the laws that govern the rounding of particles of sand. Transactions of the Edinburgh Geological Society, vol. vii, 1897, p. 300. See also paper by Goodchild (loc. cit.), 1896, p. 208. Also On the constitution and history of grits and sandstones, by Phillips. Quarterly Journal of the Geological Society of London, vol. xxxvii, 1881, p. 21.

traveled to be uniform, the author constructs a table showing the relative *roundability* ("psephicity") of the common rock-forming minerals for both water and air. Although the figures must be regarded as only approximations, they are of interest in connection with the present discussion, and a portion of the table is here reproduced.

Mackie's Table showing the relative Capacity of Minerals to become rounded.

Mineral.	In water.	In air.
1. Quartz	.23	.38
2. Orthoclase	.29	.40
3. Labradorite	.29	.45
4. Hornblende	.39	.57
5. Biotite	.70	1.05
6. Muscovite	.86	1.30
7. Magnetite	.70	.86
8. Garnet	.39	.53
9. Tourmaline	.30	.43
10. Zircon	.45	.59
11. Rutile	.51	.68

These figures are to be interpreted as meaning that the capacity for being rounded in water is about 1 2/3 times greater for hornblende and garnet grains than for quartz, providing the grains are of approximately the same size and shape and have been subjected to the same amount of water action.

In comparison with glacial and residual sands and many samples of the volcanic type, the aqueous sands show marked evidence of erosion about the corners and edges. When the action has been relatively slight in amount the quartz grains, however, as well as garnet, magnetite, and some other harder minerals, may show sharp points and edges and fresh conchoidal fracture (see figures 1 and 2, plate 44). Much variety of material is to be expected, especially if the granules are derived from glacial or residual deposits. Subjected to further action, the softer, cleavable, and slowly soluble or decomposable minerals begin to be reduced in size and gradually eliminated, while the harder show evidence of wear (see figures 3 and 4, plate 44). In a paper presented to the Edinburgh Geological Society, in 1896, Mackie describes the gradual elimination of feldspar from the river sands, samples for study being collected from various points along the courses of the streams.[16] In the case of the four principal rivers studied the average amount of feldspar

[16] Mackie: The sands and sandstones of eastern Moray. Transactions of the Edinburgh Geological Society, vol. vii, p. 148. See also "Studies for students," by Barrell. Journal of Geology, vol. xvi, 1908, p. 364.

left in the river sands taken from points nearest the sea was 18 per cent, while the neighboring sea sands were found to contain but 10 per cent (page 149). The common minerals, softer than the feldspars, would be disposed of still more promptly, and there results a gradual concentration of the quartz granules because of its hardness, specific gravity, lack of cleavage, insolubility, and ability to resist decomposition. Work of a similar nature has been done also by Walther in the way of showing that the softer and more decomposable minerals are slowly eliminated in the course of a stream leading to a concentration of quartz. In proportion to the amount of water action to which they have been subjected these quartz grains become smoothed, present rounded edges and corners, and assume subangular outlines. By subjecting angular fragments derived from crushed granite to an experiment in which the distance traveled could be approximately determined, Daubrée found that in a distance of about 15½ miles these fragments were indistinguishable from common river sand. The investigations of this able experimenter showed further that granules .1 millimeter in diameter will float in feebly agitated water, from which he concluded that grains of this size and less could not be mechanically rounded by water action.[17] When such are found in aqueous deposits the inference is that they are of other origin.

An interesting pure gray sand, which seems to have been due to very long continued water action, is found on the Gulf of Mexico coast, Escambia County, Florida. There is scarcely a fragment left of any mineral other than quartz showing practically perfect concentration, while the granules evince long continued wear, but are still subangular in general outline rather than subspherical or ellipsoidal (see figure 4, plate 44). This sand is briefly described under the head of "Gray Sand" in the Second Annual Report of the Florida Geological Survey, 1909, page 152. A mechanical analysis of this sand by the U. S. Bureau of Agriculture shows that practically all material below .1 millimeter has been removed (presumably by assorting action), and that the granules range from .1 millimeter to 1 millimeter in diameter, averaging from .25 to .50 millimeter.[18] It would be of interest to know the distance that this material has been transported and the original source of it, but so far this is unknown. Under date of May 14, 1910, State Geologist E. H. Sellards writes that he regards the mantle of sand over the interior of the state of Florida as *residual* and resulting from the decay of originally existent sand-bearing formations. As to that of the highlands of Escambia

[17] Geologié Expérimentale, p. 256.
[18] Reported in correspondence by E. E. Free, physicist of the department.

County, from which the beach sands of this portion of the gulf were probably derived, he writes:

"The considerable depth of sand forming the top part of the section along the bluffs facing Pensacola Bay, these sands are of the type that I regard as residual. The upper several feet are bleached white. Such iron staining as they may have possessed originally is likewise carried away through the leaching effect of rain water. Our summer rainfall is extremely heavy, and the minute clay particles which originally formed part of the formation have been carried away by mechanical wash. Beneath these light colored superficial sands is found the sand in less complete condition of decay, at this depth being mottled, iron-stained, and containing more or less fine clay mixed with the sand. . . . It appears to be a formation originally deposited in comparatively shallow water with conflicting currents, resulting in irregularities in deposition and in cross-bedding. The materials doubtless came from the continent to the north. . . . The nearest igneous rocks which must have been their original source lie some 500 miles to the northwest."

According to this interpretation, the Escambia beach sand is being the second time worked on by the waves, the residual agencies just preceding presumably having had little effect upon the granules themselves. It appears to represent the extreme type of aqueous sand. Merrill has briefly described and figured what appears to be an identical sand from the beach of the neighboring Santa Rosa Island.[19] At West Palm Beach, on the Atlantic side of the state, there occurs the same type of sand, which has been presumably transported many miles along shore from the Piedmont region to the north, yielding the subangular type of granule and eliminating practically everything but quartz.[20]

In glaciated and adjacent regions the bulk of the sand handled by streams and the waves of the lakes and seas is very probably of glacial origin, while in non-glaciated areas it is either largely residual or derived from the parent beds directly by the erosive action of the water itself. For volcanic sands rehandled by the water the compound term aqueo-volcanic is expressive, but is not intended to be applied to a sand resulting from the direct action of water on an ordinary lava bed. It is scarcely to be expected that volcanic sands of the rounded type can be distinguished from aqueo-volcanic sands except by evidence based on the nature of the depositing agent. About the shores of volcanic islands aqueo-volcanic sands must occur not infrequently, and in cases such as clearing their valleys of the vast quantities of ash derived from La Soufriere, in 1902, the Wallibu and Rabaka rivers, on the Island of Saint Vincent,

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[19] Rocks, rock-weathering, and soils, p. 343.

[20] See Shaler's paper, "Phenomena of beach and dune-sands." Bulletin of the Geological Society of America, vol. 5, 1894, p. 208.

have rehandled and assorted much sand and without doubt modified the form of granules.[21] Subjected to the various agencies of weathering, a bed of aqueous sand or a bed of sandstone derived therefrom, such as that referred to above in connection with the Escambia sand, may gradually assume residual characteristics and be conveniently classified as residuo-aqueous. The quartz grains will undergo but little change in size, form, or condition unless organic acids are present, but they may become much stained and rusted from contact with other minerals. They may be relied on to indicate the aqueous origin of the bed and to thus distinguish it from the simple residual type of sand. The cleavable and decomposable minerals, when present, will be broken up and altered and their original size, form, and condition lost. A glacio-aqueous subtype of sand results when a glacier operates with sufficient vigor on a firm sandrock originally aqueous; the granules becoming mechanically crushed will show more and more of the characteristics assigned to glacial sands. Many of the granules would be expected to retain more or less trace of their original rounded outlines not seen in ordinary glacial sands derived from the crystalline rocks, and faceting and striation could probably be detected on some of the coarser granules. In the case of such a glacio-aqueous subtype of sand the rounded granules are becoming sharply angular, while in the aqueo-glacial subtype previously referred to the edges and angles of irregular granules are becoming subdued.

Until acted on by some secondary agency, glacial, volcanic, and residual sands are generally found near enough to their home locality, so that their origin may often be inferred with reasonable certainty. In the case of aqueous sands, however, they may be transported to such distances that their place of origin can be determined, if at all, only by the most detailed study of the constituent granules. This problem was attacked some fifteen years ago by Mackie, and his observations and conclusions reported on in the paper previously cited, "The sands and sandstones of eastern Moray." From a study of the inclusions present in the quartz and feldspar granules and from the associations of minerals found to be present in the loose sands and the possible parent beds, he was able to make very plausible inferences concerning the origin of the grains of certain modern and ancient sand formations of northern England.[22] In the quartz grains three types of inclusions were recognized in that region, which, with those grains in which they were absent, gave four

[21] See paper by Hovey, "Clearing out of the Wallibu and Rabaka gorges on Saint Vincent Island." Bulletin of the Geological Society of America, vol. 20, 1909, p. 417.

[22] See also paper by Sorby (loc. cit.). Proceedings of the Geological Society of London, vol. xxxvi, p. 47.

subdivisions (page 152)—regular, acicular, irregular, and absent. The first division comprised the ordinary crystalline inclusions, such as chlorite, mica, rutile, apatite, garnet, zircon, magnetite, etcetera, which might occur in various combinations or under exceptional forms. The acicular division included those grains showing tufted, sheaf-like or other combinations of fine needle-like inclusions, some of which were identified as sillimanite. Under "irregular inclusions" are referred the gas or liquid inclusions, with or without bubbles. The author's study of the crystalline rocks of his region convinced him "that acicular and irregular inclusions preëminently abound in the quartz of granite; that the regular group is to be found in various proportions, but always in relatively larger numbers in the quartz of gneiss and the younger schistose rocks" (page 154). In tracing the sands to the parent bed on the basis of the quartz inclusions, confirmatory evidence could often be obtained from the inclusions or certain peculiarities of the associated feldspar or other minerals. In summarizing his success in applying the method, Mackie says: "Several groups have been identified with all but absolute certainty. Regarding others, which may be traced to more than one locality, there is, of course, at times some doubt, while regarding a considerable residuum I have not yet even a hint to go by in the matter of their identification" (page 158). This work and the method employed suggests many problems awaiting solution in all sections of the country. An attempt to utilize the method in tracing the origin of the Sylvania sand is given toward the close of this paper.

Æolian Sand Types

Sands of any of the previously described types—glacial, volcanic, residual, and aqueous—may come within the grasp of the winds, and suffer still further abrasion under the influence of this new agency. In comparison with the water, the granules in air strike with so nearly their full weight that the shaping of such grains is much more rapid and complete. Applying the formula previously referred to, Mackie[23] calculated that with a current velocity of 2 miles an hour and a wind velocity of 8 miles an hour, the rounding effect of the wind on quartz grains is about *twenty-nine* times greater than is that of the water, and that particles less than one-fifth the diameter of those rounded by water will be rounded to an equal extent by the wind. The factors involved in this rounding process

[23] Mackie: On the laws that govern the rounding of particles of sand, p. 310. See also

Udden: Erosion, transportation, and sedimentation performed by the atmosphere. Journal of Geology, vol. ii, 1894, p. 318.

are the size, hardness, and specific gravity of the granules, the total distance and the velocity with which they have been moved. Other minor factors that must be reckoned with are cleavability, solubility, tendency to decompose, ability to absorb heat and withstand sudden changes of temperature. The relative ease with which the common minerals become rounded in air, when subjected to approximately identical conditions, is shown in Mackie's table quoted on page 634 of this paper, from which it is seen that quartz is still the most resistant of the list, but differing only slightly from orthoclase.

Sand of the glacial, volcanic, residual, or aqueous type, subjected to but slight wind action, is not to be distinguished from the parent material in isolated samples. Taken in connection with the deposit, however, in which it occurs, a distinction may be made and the prefix *æolo* utilized. Furthermore, the evidence of æolian erosion often may be recognized, superposed on the original granule, but without obliterating its main features. To the extent that loess possesses a texture comparable with sand (ordinarily it is much finer) and is derived from glacial deposits by wind action, it represents an æolo-glacial subtype. So far as it may have been deposited by the action of water it would come under the head of an aqueo-glacial deposit.[24] If the material was largely residual to start with, as advocated by Pumpelly for the great deposits of eastern China, and as supported by the recent researches of the Carnegie Expedition, then such loess should be characterized as æolo-residual,[25] and could probably be distinguished from that of glacial origin. Ordinary volcanic sand must more often than not have its surface layers subjected to wind action, from which there would result sand of the æolo-volcanic variety, recognizable by the composition of the granules, the more or less complete rounding of the finer materials, and the nature of the deposit in which found. Much of the sand of the Sahara and other great deserts of the earth is probably æolo-residual in character, resulting from the breaking down by wind erosion and weathering of beds of crystalline and fragmental rocks.[26] The constant supply of this material, combined with the continuation of the residual agencies, often causes a puzzling mixture of typical æolian sand and sharp, angular fragments which belong at the

[24] A description of the microscopic appearance of a loess from Muscatine, Iowa, is given by Diller in U. S. Geological Survey Bulletin No. 150, p. 65. More general descriptions will be found in the Sixth Annual Report of the U. S. Geological Survey, 1885, p. 278, by Chamberlin and Salisbury. See also McGee's paper in the Eleventh Annual Report, 1891, p. 291.

[25] Pumpelly: The relation of secular rock-disintegration to loess, glacial drift, and rock basins. American Journal of Science, 3d ser., vol. xvii, 1879, p. 133.

Willis, Blackwelder, and Sargent: Research in China, vol. i, 1907, p. 242.

[26] "Das Gesetz der Wüstenbildung," Walther, 1900, p. 120.

other extreme of the series (see figure 3, plate 45, and figure 1, plate 46). Sands derived directly from ocean and lake beaches or from river flats are seized by the winds and heaped into dunes, furnishing us abundant examples of the æolo-aqueous type of sand. These are generally referred to as "dune sands," but since they are often found not in dunes and dunes occur most abundantly and typically in desert regions, where the source and nature of the granules may be markedly different, the genetic term æolo-aqueous is to be preferred. Owing to their location, they may be returned to the water many times in their history and successively submitted to the action of current, wave, and wind. Typically these sands show a larger admixture of rounded and subangular granules than will be found in the parent beach and river sands (see figure 6, plate 44, and figures 1 and 2, plate 45). The surfaces are more generally smoothed and begin to show the appearance of ground or frosted glass, and some pitting of the surface begins to be detectable. As their name implies, they are intermediate in character between typical æolian and typical aqueous sands and may graduate imperceptibly into either, which fact will account for the somewhat conflicting statements of observers concerning beach, dune, and desert sands and the very general impression that real distinctions can not be made.

Thus far we have spoken of only those cases in which the wind action is incomplete, its effect not obliterating that of the previously operating agencies. When there is opportunity for strong and long continued wind action, without too much accession of new material, as in the case of some ancient deserts, the granules become more generally and more perfectly rounded and we have produced the true æolian type of granule (see figure 6, plate 47). The *bodies* of the granules themselves become subspherical or ellipsoidal, their surfaces are dulled, frosted, and minutely pitted, seen best in the coarser granules (see figure 2, plate 46). Zittel has described the surfaces of such granules as *polished*, but this term is inappropriate if he has in mind the granules in a dry state.[27] The fracture surfaces of the quartz granules are smoothed out, the corners and angles gone, but the surfaces are minutely rough. This rounding continues down to grains much smaller than .1 millimeter, the limit set by Daubrée for water rounding, but is not general in any desert sand examined, owing probably, as pointed out above, to accessions of new material by residual action and the continuous action of the residual agencies on the granules capable of further change. Owing to the same reason, the assorting of the grains is not as perfect as it would otherwise appear and

[27] Beiträge zur Geologie der libyschen Wüste. Palaeontographica, Bd. xxx.

the elimination of the softer minerals is not complete (see figure 3, plate 45, and figure 1, plate 46).

Owing to the action of the various residual agencies on the cleavable, soluble, or decomposable minerals, combined with the abrasion of the softer ones, they are gradually reduced to dust and blown away, leading to a more perfect assortment and a concentration of quartz, as pointed out by Walther[28] (pages 149-153). Preceding the sand storms in the Libyan desert this observer noted dust clouds which settled about the margins of the desert, and he writes:

> "It is no accident that the bed of vegetationless desert is covered with quartz sand, the bed of the grass-grown steppe with clay dust. It is also no accident that the north African deserts are surrounded by clay dust steppes. Desert and steppe belong together not only from the viewpoint of climatology, but also sedimentary formation—the steppe is often the child of the desert" (page 152).

This removal of the dust and concentration of the quartz was previously described by Sokolow[29] (page 189). In the Astrakhan region he found the sand to consist of 90 per cent quartz, with the grains rounded, irregular, and angular—those entirely rounded being rare, those entirely angular still more rare (page 188). There appears to be a type toward which the æolian sands are slowly working, but not known to actually attain in any modern desert. Such a sand would be almost perfectly assorted; would consist practically of quartz, the granules being subspherical, regardless of size; the surfaces would be dulled and pitted. Such a sand is believed to be shown in figure 6, plate 47. The size of the granules would gradually be reduced until small enough to remain suspended by the air currents, when further reduction in size by mechanical erosion would cease. Before this would happen, however, they would be swept away and would enter on another stage of geological history.

Although the assorting power of the air is superior to that of the water, the deposits resulting therefrom are less regular and even. Experiments of Sokolow (loc. cit., page 82), conducted in the laboratory on dry sand, gave an angle of rest ranging from 30 to 40 degrees. If 40 degrees was exceeded the sand was very unstable, and became less in case of rounded granules. His observations of the angles maintained on the lee side of dunes ranged from 29 to 32 degrees. Other observers are quoted: Forchammer having obtained 30 degrees; Andreson, 28 to 31

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[28] Walther: Die Denudation in der Wüste und ihre Geologische Bedeutung, Abhandlungen der mathematisch physischen Classe der Königl. Sächischen Gesellschaft der Wissenschaften, Band xvi, No. III, 1891. See also Udden: Dust and sand storms in the west. Popular Science Monthly, vol. xlix, 1896, p. 655.

[29] "Die Dünen, Bildung, Entwickelung und innerer Bau," 1884. Translated from Russian into German by Arzruni, 1894.

degrees; Raulin, 28 to 32 degrees, and Hagen, 26.5 to 31.5 degrees. Angles reported as high as 50 to 60 degrees he regards as simply eye estimates. In the case of the lee slopes of the dunes of the Oregon coast Diller reported angles of 40 degrees.[30] In the case of dunes, the angle of the lee slope may be reduced by rain or other causes. Owing to these high angles of rest and the varying velocity and direction of the winds, steep cross-bedding and irregular stratification are common and characteristic.[31] In a recent discussion of this subject, Barrell gives the following needed help to distinguish æolian from aqueous deposits: "The characteristic features of such dune sands, separating them from fluvial or littoral deposits, consist consequently in the homogeneous nature, the development of 'millet seed' texture, and the presence in striking degree of cross-bedding which may reach great thicknesses. The cross-bedded strata are abruptly truncated above but flatten out and become tangent to the general stratification at the bottom."[32]

Rippling may occur in æolian sands, as in those of aqueous origin, but according to Goodchild, in the case of the former the coarser granules occupy the *crests* of the ripples, whereas in the latter they are found in the troughs.[33] Coarse gravelly deposits, interbedded with æolian strata and believed to be of torrential origin, have been described by Walther and Goodchild. Owing to the general absence of material capable of forming a cement, an æolian bed would be expected to form a very incoherent type of sandrock unless the granules were bound together by foreign material secondarily introduced, such as silica, alumina, calcium or magnesium carbonate, iron oxide, carbonaceous matter, etcetera. Fossils would scarcely be expected, but, if present, should be of the land type, and introduced during a more or less stagnant condition of the sand giving rise to the deposit.

Æolian sands may be subjected to the previously described agencies, and new subtypes thus originated. Glacio-æolian sand would result from the passage of a glacier over a consolidated æolian sandstone, detaching and crushing the granules as described for the glacio-aqueous subtype. Residuo-æolian sand would result when such a bed is exposed for a sufficient time to the agencies of weathering, the quartz granules being isolated by the solution of the cementing material and the decomposable

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[30] Seventeenth Annual Report of the U. S. Geological Survey, part 1, 1896, p. 450.

[31] See Walther: "Die Denudation in der Wüste," p. 172.

[32] Barrell: Relations between climate and terrestrial deposits. Studies for students. Journal of Geology, vol. xvi, 1908, p. 282.

[33] Goodchild: Desert conditions in Britain. Edinburgh Geological Society, vol. vii, 1896, p. 212. A very satisfying discussion of rippling and dune formation has been given us by Cornish in the Geographical Journal, vol. ix, 1897, p. 278. See also Chamberlin and Salisbury: Geology, vol. i, chapter ii, p. 20.

minerals beginning their processes of decay. If iron is present in these minerals or is secondarily introduced in any way, the quartz granules will become coated with yellow, brown, or red oxide. What is apparently such a sand has been described by Phillips under the title, "The red sands of the Arabian Desert."[34] The surface features of this desert appear to be in a state of repose, as evidenced by the sprinkling of vegetation, by objects left on the surface remaining uncovered for years and the fact that the same landmarks can be constantly used in crossing. The quartz grains are well rounded and coated with a deposit of ferric oxide, giving the sand a light red color, described as almost crimson when wet with dew in the early morning. The English Bunter sandstones, of Triassic age, have been assigned an æolian origin by Phillips and are plainly of the residuo-æolian subtype, judging from the following description:

"Reddish-brown friable beds, possessing but little cohesion, and of which the constituent grains are all so completely rounded, that the disintegrated sand flows between the fingers as readily as shot. . . . These grains, of which the majority are quartz, are so rounded as to represent miniature pebbles, while a few, consisting of partially decomposed felspar, are often corroded into deep cavities on one or more of their sides."[35] This is one of the so-called "millet-seed" types of sandstone.

As the result of stream or wave action on an æolian deposit, ancient or modern, the aqueo-æolian subtype of sand would be formed. If kept free from admixture with other aqueous material, which would not ordinarily be the case, it is not apparent that any special change would occur in the character of the granules. If found in the water itself, the more perfected character of the granules would suggest an æolian origin, while if already deposited the nature of the stratification, the character of the cement, or the presence of water fossils would point toward its aqueous relationship. This is illustrated very satisfactorily by portions of the Sylvania formation, to be presently described.

Organic Sand Type

Unless it is remembered by the reader that the classification here adopted is based on the agency or agencies concerned in sand production, and not on its composition, the term *organic* will prove misleading.[36]

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[34] Quarterly Journal of the Geological Society of London, vol. 38, 1882, p. 110.

[35] Phillips: On the constitution and history of grits and sandstones. Quarterly Journal of the Geological Society of London, vol. xxxvii, 1881, pp. 12-13.

[36] It may be noted, however, that sand of organic *composition*, if found to exist, would also be included under this same heading. It is conceivable that granules of suitable texture might be locally segregated consisting of coal, asphaltum, fossil spores, amber, evaporated petroleum, etc.

Under this head it is proposed to group those sands which owe their origin and character of grain to animal or plant life, either during the life of the organisms or subsequently. The composition of the material is mainly calcareous (calcite or aragonite) or silicious, and was extracted by the organisms from the water in which it was held in solution. Here belong typically the accumulations of the finer varieties of molluscan shells, along with the coarser forms of foraminifera and radiolaria.[37] The so-called "green sand," a composite of many minerals, chief of which is glauconite, owes its composition, in part, as well as its form, to foraminifera, the granules having been moulded inside the empty shells. The generally accepted view is that the glauconite results from the organic reaction of the decaying life on muddy sediments derived from the land. Much of this has formed in the past, especially during the Cretaceous, and it is still forming in the ocean at depths of 100 to 200 fathoms. The granules are rounded, sometimes mammillated and nodular, often coarse, but mingled with much fine material.[38] So far as shell marl is of suitable texture or contains such portions, to be considered as sand it would belong under this heading, whether derived from shells or from the growth of lime-secreting plants, as shown by Davis.[39] This author points out that the upper portions of marl beds often have such sandy textures, composed of the incrustations that form on the stems of *Chara* (page 493). To the work of this plant and to that of blue-green algæ (*Zonotrichia* and *Schizothrix*), which secrete calcium carbonate, is ascribed the production of marl. The two latter algæ give rise to incrustations of spongy material over dead bivalve shells of inland Michigan lakes and over those portions of live forms not embedded in the sand. They also form ellipsoidal, calcareous pebbles of spongy nature, showing both a concentric and radial structure, as described by Davis. These are readily disintegrated by wave action into sand, assorted, and the fragments often made into a beach. By this wave action the coarser shells, the corals, bryozoa, echinoid and crinoid fragments, are broken up and comminuted into sand, the edges more or less rounded, and there results the aqueo-organic subtype of sand[40] (see figure 3, plate 46).

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[37] Hinde and Fox: On a well marked horizon of radiolarian rocks, etc. Quarterly Journal of the Geological Society of London, vol. li, 1895, p. 609. Also Evans: Mechanically formed limestones from Junagarh and other localities, vol. lvi, 1900, p. 576.

[38] Murray and Renard: Challenger report on deep sea deposits, 1891, pp. 239 and 387. Also

Clark: Annual Report of the State Geologist of New Jersey for 1892, part ii, 1893, p. 218.

Diller: Bulletin No. 150, U. S. Geological Survey, 1898, p. 63.

[39] Davis: A contribution to the natural history of marl. Journal of Geology, vol. viii, 1900, p. 485. Also vol. ix, 1901, p. 491. Geological Survey of Michigan, vol. viii, part iii, 1903, p. 65.

[40] See Sorby in Proceedings of the Geological Society of London, vol. xxxv, 1879, p. 69.

The agency of vegetation in causing granular deposits in hot springs was first pointed out by Cohn in 1862, in the celebrated Carlsbad waters.[41] The granules of calcium carbonate become gradually coarser, and are finally united into a compact bed of travertine. Seeley, in 1888, called attention to the close resemblance between oölitic granules and the inter-nodal grains of certain nullipores, and suggested this as a possible origin of some beds of oölite.[42] The studies of Weed in the Yellowstone National Park led him to the same conclusion as Cohn concerning the origin of the calcareous formations about the Mammoth Hot Springs.[43] Pellets up to 1 millimeter in size form within the tissues of the algæ and are finally cemented together and their outlines lost. The same cause was also found operating in the geyser regions, the plants being both algæ and moss, and leading to the deposition of silicious sinter (page 665). Owing to the porous, incoherent, often mealy nature of these calcareous and silicious deposits, they are readily disintegrated again into sand and coarser fragments, giving rise to a residuo-organic subtype of sand. To the extent that calcareous tufa and travertine, deposited so commonly from ordinary spring water, may be found due to plant agency, these deposits would belong under this same division.

Of essentially the same nature is the oölitic sand of Great Salt Lake, Utah, which was made the subject of study in 1891 by Rothpletz, of Munich, who concluded that the granules originated in the tissues of colonies of bluish-green algæ (*Glœocapsa* and *Glœothece*) and are now forming.[44] Samples of this sand were studied and described by the present writer in 1899, and the conclusion reached that the Monroe oölites of southeastern Michigan must have had a similar origin.[45] The Salt Lake granules are well asserted, grayish white and mottled in color, about .3 to .4 millimeter in diameter, the outer surfaces so smoothed and polished that they resemble porcelain, and made up of concentric layers of calcium carbonate, showing more or less radial arrangement. There is no nucleus of quartz or other mineral present but what appears as an organic core. Elongated, stick-like forms are mingled with the granules, straight or slightly bent, with rounded ends and otherwise resembling the granules themselves. Less frequently there occur much larger, flattened masses

[41] Cohn: Die Algen des Karlsbader Sprudels, mit Rücksicht auf die Bildung des Sprudel Sinters; Abhandl. der Schles. Gesell., part ii, p. 35.

[42] Seeley: On the origin of oölitic texture in limestone rocks. British Association for the Advancement of Science, Bath meeting, 1888, p. 674.

[43] Weed: Formation of travertine and siliceous sinter by the vegetation of hot springs. Ninth Annual Report of the U. S. Geological Survey, 1889, p. 619.

[44] Rothpletz: Ueber die Bildung der Oölithe. Botanisches Centralblatt, vol. li, 1892, p. 267. Translation in American Geologist, vol. x, No. 5, 1892, p. 279.

[45] Michigan Geological Survey, vol. vii, part i, 1900, p. 64.

of irregular shape, with tubercular surfaces (see figure 4, plate 46). Rothpletz reached the conclusion that

"The oölites of the Great Salt Lake are, therefore, indubitably the product of lime-secreting fission-algæ, and their formation is proceeding day by day. . . . According to the present stage of my researches, I am inclined to believe that at least the majority of the marine calcareous oölites with regular zonal and radial structure are of plant origin: the product of microscopically small algæ of very low rank, capable of secreting lime."[46]

Wethered had ascribed a similar origin to pisolitic granules from near Weymouth, England, some three years earlier, attributing them to the action of a tubular organism *Girvanella*.[47] In 1895 this same author presented to the Geological Society of London a paper entitled "The formation of oölite,"[48] in which the organic origin of oölite was advocated. Weed suggests, in the way of explanation of the deposition of calcium carbonate by green plants (loc. cit., page 642), that their withdrawal of carbon dioxide (for photosynthesis) from the water would reduce its ability to retain the carbonate in solution and lead to its deposition. This explanation seems plausible, but does not explain the silica-secreting power of other plant forms, and leaves the question in doubt. Oölitic granules occur in which the calcium carbonate has been replaced by silica, dolomite, or iron oxide,[49] and all belong under this subdivision of sands, since the form of the granules, aside from the composition, is still due to the original organic agency.

When any of the various varieties of organically produced sands are subjected to wind action, æolian deposits may be formed similar to those already described. Furthermore, the same kind of changes would occur in the component granules, so far as the nature of the material would permit. The oölitic granules, already so perfectly rounded, would lose their polish and simply suffer reduction in size. Such sands would constitute the subtype of æolo-organic, interesting examples of which are known—as those of the Bermuda and Bahama coasts, described by Nelson.[50] On the former island great dunes occur, some 200 feet in height, composed of fragments of corals, shells, etcetera, and the products of

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[46] American Geologist, loc. cit., pages 280 and 282.

[47] Wethered: On the microscopic structure of the Jurassic pisolite. Geological Magazine, 1889, new series, vol. vi, p. 196.

[48] Quarterly Journal of the Geological Society, vol. li, 1895, p. 196.

[49] Goodchild: The origin of hematite. Transactions of the Cumberland and Westmoreland Association, No. viii, 1883, p. 117.

[50] Nelson: On the geology of the Bahamas and on coral formations generally. Quarterly Journal of the Geological Society of London, vol. ix, 1853, p. 200. Bermudas described in Transactions, ser. 2, vol. v, part i, 1837, p. 103. See also Darwin's "Corals and coral islands," 1872, pp. 152 to 156.

lime-secreting plants. Portions are so firmly cemented into a coquinaceous sandrock as to be utilizable for building purposes. The Bahamas furnish similar deposits; also the shores of the Red and Arabian seas. The southwestern coast of Galway, Ireland, contains low dunes made up largely of foraminiferal material, with other calcareous fragments, described by Evans, along with other similar deposits.[51] The author considered that the Great Oölite formation (Jurassic) of England had resulted from the accumulation of wind-blown oölitic granules, interbedded with littoral deposits (page 580).

Concentration Sand Type

This term, perhaps not the happiest that can be found, is used to designate a type of sand resulting from the concentration of solutions by evaporation, or by chemical action whereby the same result is achieved. From this method of formation the material will be generally crystalline in structure, the growth taking place from within, outward about a center, so that the connotation of the term selected for the type is not inappropriate. In this manner of formation the concentration granules are distinguished from all other types, except certain ones belonging to the organically formed division. When these minerals are deposited in granular condition, or reduced to such, they may be collected by wind action and form extensive deposits in arid regions. Near Alamogordo, New Mexico, there occurs an immense deposit of gypsum sand reported to be some 300 square miles in area. A sample shows it to be practically pure gypsum, of creamy white color, the granules being very generally rounded, but where broken along the cleavage planes showing fresh edges (see figure 5, plate 46). Crushed between the fingers it is reduced to fine, angular fragments. These deposits have been recently figured and described by MacDougal in publication No. 99 of the Carnegie Institution, 1908, page 11, and a chemical analysis given. In the paper just referred to by Russell smaller but similar gypsum dunes are mentioned as located near Fillmore, Utah. Deposits of salt in granular condition may form in arid regions around the margins of salt lakes, such as

[51] Evans: Mechanically formed limestones from Junagarh and other localities. Quarterly Journal of the Geological Society of London, vol. lvi, 1900, p. 559. This paper contains a full list of references treating of æolian action on calcareous fragmental deposits. See also, in same volume, Chapman's paper, "Notes on the consolidated æolian sands of Kathiawar," p. 584. In a paper entitled Subaërial deposits of the arid region of North America, Russell mentions low dunes in the Carson Desert of Nevada made up entirely of casts of a small crustacean—*Cypris*. Geological Magazine, new series, vol. vi, 1889, p. 289.

that described by Darton in New Mexico.[52] It is possible that it might be locally accumulated into heaps of salt sand by wind action, although this result would be resisted by the attraction that the salt has for moisture. A similar occurrence of epsomite (magnesium sulphate) has been noted in California by Major Emory,[53] and that of mirabilite (sodium sulphate) by Talmage about Great Salt Lake, resulting from a lowering of the temperature.[54] It seems probable that granular deposits might also be similarly formed of numerous other minerals, more or less soluble in water, such as borax, alum, magnesite, chloromagnesite, thinolite, dolomite, aragonite, calcite, etcetera.[55]

To the extent that the deposition of calcareous tufa, travertine, and silicious sinter results from the relief of pressure, loss of carbon dioxide, cooling or evaporation, combined with the vegetable agencies enumerated, we have a deposit of the organo-concentration subtype which might be of granular texture or easily reducible to such. If there are oölites formed, as described by Sorby,[56] by "the original deposition of calcite round nuclei gently drifted along by currents of the ordinary temperature, which caught up more or less of the surrounding mechanical impurities," such a result could be secured only in a concentrated, and hence over-saturated, solution of calcium carbonate. Our classification would thus separate the organically formed oölites from those due to over-saturation, as it very obviously should do, providing there is this essential difference in their mode of formation. The oölitic iron ore of the Clinton formation of New York is regarded by Smyth as not due to the replacement of calcareous granules by iron oxide, but to the formation of original deposits of silica and oxide concentrically about rounded grains of quartz as nuclei. This mode of origin, without the agency of vegetation, would demand a certain degree of concentration of the solution furnishing the materials.[57] A silicious oölite from Center County, Pennsylvania, has

[52] Darton: Zuni salt deposits. Bulletin No. 260, U. S. Geological Survey, 1905, p. 565. See further, "Lake Bonneville," by Gilbert, Monograph I, U. S. Geological Survey, 1890, pp. 208 and 257, and "A description of the Salt Lake of Larnaca, in the Island of Cyprus," by Bellamy. Quarterly Journal of the Geological Society of London, vol. lvi, 1900, p. 745.

[53] American Journal of Science, 2d ser., vol. vi, 1848, p. 389.

[54] Talmage: The waters of Great Salt Lake. Science, vol. xiv, 1889, p. 446.

[55] An interesting discussion of the subject of chemical concentration will be found in Russell's presidential address, prepared for the Geological Society of America in 1906, "Concentration as a geological principle." Bulletin of the Geological Society of America, vol. 18, 1907, p. 12. See also his monograph on Lake Lahontan, U. S. Geological Survey, No. xi, 1885, from p. 182, and following.

[56] Proceedings of the Geological Society of London, vol. xxxv, 1879, p. 75; see also "Mechanically formed limestones from Junagarh and other localities," by Evans, vol. lvi, 1900, p. 559.

[57] American Journal of Science, 3d ser., vol. xliii, 1892, p. 487. Reviewed in American Geologist, vol. x, 1892, p. 122.

been described by Hovey as consisting of fibrous chalcedony about quartz fragments or aggregations of very fine sand particles, the concentric deposits taking place about the nuclei in hot silicious waters.[58]

This would seem the proper place to describe a type of sand resulting from the secondary enlargement of quartz grains formed by any of the preceding agencies. About the original granule as a nucleus a shell of crystalline silica is deposited in optical continuity with that of the original grain, giving sharp, fresh crystal facets and edges and generally showing the double, pyramidal terminations (see figure 6, plate 46). This condition of the Sylvania granules was recognized as early as 1840 by Bela Hubbard, assistant on the Michigan Geological Survey,[59] but without any attempt at explanation. This was probably the first recognition in this country of this type of sand grain, although it had been earlier noted in Europe by numerous observers and generally regarded as of chemical origin. Sorby described similar grains in 1880 from the New Red Sandstone of Penrith, England,[60] and noting the impressions due to the interference of contiguous grains, concluded "that the deposition of crystalline quartz took place after the nuclei were deposited as a bed of normal sand" (page 63). Similar grains were described and figured by Irving from the Huronian, Potsdam, and Saint Peter formations of Minnesota, Wisconsin, and Michigan,[61] and the importance of this action pointed out in the transformation of sandstones into quartzites (page 224). Subsequently a paper on the subject of secondary enlargement of quartz grains was presented to the Geological Society of London by Wethered.[62] The secondary silica he regarded as having been "extracted from solution by the molecular affinity between the silica of the detrital quartz and the silica in solution" (page 196). A later reference to the subject and some clear figures will be found in Van Hise's "Treatise on metamorphism"[63] (page 619). All who have written on the subject since the paper of Sorby was presented are agreed that the growth of the granules has taken place *in situ* from water carrying silica in solution and presumably more or less concentrated. The widespread character of the phenomenon and the conversion of so many sandstones

[58] American Geologist, vol. xiii, 1894, p. 223.

[59] Third Annual Report of the State Geologist, 1840. House Document No. 27, vol. ii; Senate Document No. 7, vol. ii; also separately, No. 8.

[60] Proceedings of the Geological Society of London, vol. xxxvi, 1880, p. 62.

[61] Fifth Annual Report of the U. S. Geological Survey, 1885, p. 218. This paper contains a list of references to the literature of the subject. See also earlier paper by same author "On the nature of the induration in the Saint Peters and Potsdam sandstones," etc. American Journal of Science, 3d ser., vol. xxv, 1883, p. 401.

[62] Quarterly Journal of the Geological Society of London, vol. xliv, 1888, p. 186.

[63] Monograph XLVII, U. S. Geological Survey, 1904. See also American Geologist, vol. xiii, 1894, p. 225, for short article by Calvin.

into quartzites through the operation of the process give it great geological importance.

Application to the Sylvania Sandstone

Having thus presented the criteria by which the seven main types of sand grains, with all the intermediate subtypes, may be recognized, it will be of interest to make an application of the principles to a specific case. The formation selected is the Sylvania sandstone, first very briefly described by the early Michigan and Ohio surveys, and then more fully by Orton[64] and the present writer.[65] The formation was supposed for many years to represent the Oriskany in the Lake Erie region, but is now known to be of mid-Monroan (Silurian) age, separating the lower dolomites from those of the upper division. In a bulletin about to be issued by the Michigan Geological Survey, treating of the Monroe Formation, prepared by Prof. A. W. Grabau and the writer, the results of detailed studies of this bed will be presented. Only those features need be mentioned here which throw light on the origin of the granules and the method of their accumulation. The sandrock is a remarkably pure, incoherent, snow-white aggregation of quartz granules in crystalline condition. Practically the only other minerals present have been secondarily introduced, such as calcite, dolomite, iron oxide, and additional silica, and the sand when washed can be utilized in the manufacture of high-grade glass. The granules are under a millimeter in diameter, and in the case of 14 samples studied at the Michigan Agricultural College averaged .2 to .4 millimeter. In certain samples the assorting is surprisingly perfect (see figure 6, plate 47), and in all cases the granules are rounded, continuing down to those under .1 millimeter (see figures 3 and 4, plate 47).

From this much of the description, by a process of elimination we may begin to locate the type of sand with which we are dealing. On the basis of the form and assortment of the granules we may at once rule out the glacial, residual, and much of the volcanic types, while on the basis of composition and crystalline condition the organic and remainder of the volcanic would be stricken out. Many of the grains show secondary enlargement (figure 6, plate 46), with perfect crystal facets and sharp edges, giving the sand a fresh, sparkling appearance. There is no evidence of erosion subsequent to the deposition of the secondary silica, and when embedded in a dolomite matrix, as in the case of one bed, the silica

[64] Ohio Geological Survey, vol. vi, 1888, p. 18. Also vol. vii, 1893, p. 17.

[65] Geological Survey of Michigan, vol. vii, part I, 1900, p. 53.

of the granules shows the imprints of the microscopic rhombohedrons of the dolomite, thus proving that the enlargement of the original quartz granules took place *in situ.* This phenomenon indicates that we have had the principle of *concentration,* operating on either an aqueous or æolian type of granule—but which? There's the rub!—and there is so much of it in evidence that a decision can be reached with reasonable certainty. When not secondarily enlarged the Sylvania granules are found to be all rounded, large and small, the rounding involving the real bodies of the grains and not confined to the edges and corners (see figures 3, 4, 5, and 6, plate 47). The surfaces of the coarser granules are very characteristically frosted and pitted to an extent seen only in desert sand. Indeed, this sand in its purity, degree of rounding, and assortment has attained a degree of perfection that is being constantly approached, but never attained by any known modern example. It out-Saharas the Sahara! This perfected character of the Sylvania granules can be understood when the probable history is known, a lengthy and repeated buffeting with wind and wave, with no opportunity for the accession of new material and with a mineral substance inert to residual action. The studies on the Escambia, Santa Rosa, and Palm Beach sands of Florida indicate that the elimination of minerals other than crystalline quartz may be quite as perfect for aqueous sand as for æolian (figure 4, plate 44), but that there is developed a plainly different type of granule.

Search must be made for field evidence, confirmatory or otherwise, of the hypothesis of the æolian origin of the Sylvania deposit. In the way of confirmation it may be said that there is an irregular stratification indicated in all the exposures, the strata changing materially in thickness within short distances; the cross-bedding is general and pronounced, the steeper angles observed ranging from 28 to 32 degrees. In places the cross-bedded layers, when followed downward, are seen to curve around and become tangent to the stratification, mentioned by Barrell on page 642 of this paper, as characteristic of æolian deposits. Steeply inclined, oblique partings occur in the deposit, not conforming with the cross-bedding nor the stratification, which may represent, so far as they are not joints, the inclined surfaces of the dunes at various stages. Considerable irregularity in the thickness of the formation is to be noted within short distances. From the Ohio line northward into Michigan it grows thicker, becoming 288 feet thick at Milan, averaging in the Solvay wells at Detroit 93.5 feet, then disappearing rather rapidly and being represented by a silicious dolomite, from which the characteristic Sylvania granules may be extracted by the use of acid. A similar dolomite is found in the

Sylvania area embedded in the sandrock, carrying marine fossils, and may be explained as formed during a temporary encroachment of the sea, the granules being distributed through it by wave action or by winds from the neighboring lands. There is a general absence of cementing material in the main body of the Sylvania, except what has been secondarily introduced (figure 3, plate 47), and the rock is characteristically incoherent, crumbling readily in the fingers. At Rockwood, Michigan, the rock is disintegrated by water from a hose, and while in suspension pumped from the quarry. The assorting of the grains is marked, both horizontally over the area and vertically in the bed, and, excepting near the base at a few points, have any granules been observed that could not have been readily handled by the winds. Such gravelly material was reported in the Milan well,[66] and in Sandusky County, Ohio, by Winchell, where the bed has thinned to but a foot and contains pebbles three-quarters of an inch in diameter.[67] This coarser basal deposit is to be expected, and may be interpreted as the beach deposit formed at the stage when the land was emerging from the sea and due to regressive overlap.[68] Except for the bed of intercalated dolomite just mentioned, and a few inches of horizontal strata at the top, fossils are entirely absent from the formation. That the sandrock was capable of retaining casts of fossils is shown by the fact that marine mollusca are abundantly indicated in the uppermost strata, combined with considerable carbonaceous material, presumably due to plant growth. This, again, we should expect, since at the time of final submergence by the sea the sand would be rearranged by the waves and an opportunity offered for the introduction of animal and plant life.

One further point remains to be noted. In discussing "Desert conditions in Britain," in 1896, Goodchild considers all areas of "inland drainage" as representing desert conditions,[69] and, based on figures of Murray,[70] estimates that such areas today, when compared with those of oceanic drainage, are about as one is to fourteen. From this we are led to inquire whether we should not expect to find in the strata of the earth's crust, more frequently than is recognized (say one-twelfth to one-fifteenth as often as the marine), evidence of subaërial deposits. Such deposits, to be sure, are liable to be subsequently destroyed by wave action, will be relatively meager in bulk, and will not invite attention because of their

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[66] Annual Report of the Geological Survey of Michigan for 1901, p. 219.

[67] Geological Survey of Ohio, vol. i, 1873, p. 603.

[68] See Grabau: Types of sedimentary overlap. Bulletin of the Geological Society of America, vol. 17, 1906, p. 613.

[69] Edinburgh Geological Society, vol. vii, p. 203.

[70] Quoted from Royal Scottish Geographical Magazine, vol. iii, p. 75.

paucity of fossils. Goodchild concludes, "with a tolerable amount of certainty, that any sandstone largely composed of well rounded grains of sand represents a desert sand, and was formed under arid conditions, on a land surface" (page 211). Accordingly he assigns such an origin to the Torridon, Old Red, and New Red sandstones of Great Britain.

In the Lake Erie region the open-sea conditions of the Niagara period were succeeded by those under which there was deposited extensive beds of salt and gypsum, marking the Salina formation and indicating, it is believed, a period of great dessication and aridity of climate,[71] but with no suggestion of actual emergence of the land. Following the Salina deposits, there succeeds those of the lower Monroe, formed of compacted gypseous, dolomitic slime, free from land detritus, becoming characteristically brecciated, and sometimes conglomeritic, showing ripple-marks, mud cracks, carbonaceous matter, and beds of oölite essentially like that forming about the shores of Great Salt Lake. This certainly indicates a shallowing of the sea at mid-Monroan time and probably a continuation of the arid conditions.[72] The upper Monroe series shows shallow submergence again, passing into the clear, open-sea conditions of the Corniferous. There is thus furnished conclusive evidence of a general movement in lower Monroe time *toward* emergence of the land and in upper Monroe time *away* from emergence. If there is any one place in the geological scale of this region, then, where we may reasonably expect subaërial deposits to be found, it is in mid-Monroan time, and here occurs the singular deposit of pure quartz sand, difficult, indeed, to account for on any other than an æolian hypothesis.

A careful search has been made for field evidence that could not be reconciled with the æolian hypothesis, but so far nothing has been found. Criticisms have been invited from those familiar with the formation, and the following received: If there was a shore near, should there not occur in the sand clastic grains of dolomite, this being the rock on which the deposit rests? Why did not the land surface contribute other material than quartz to the Sylvania formation? Why is the Sylvania not somewhat red, as in the case of desert sands today? As to the first of these three queries, it may be said that such clastic grains, if introduced, would be relatively small in amount and soon be ground to powder, in the same way that the Portland cement "cinder" is reduced between quartz pebbles. In this condition it would be removed by wind action or by percolating water in solution, traces of which are abundant in the bed, but probably of much later introduction. Concerning the second question,

[71] See Lane in vol. v, Michigan Geological Survey, 1895, part ii, p. 28.
[72] Geological Survey of Ohio, vol. vii, 1893, p. 15.

it may be pointed out that there were no crystalline formations capable of supplying other minerals between the present deposits and their supposed parent bed. Those materials that could have been thus supplied would have been reduced to powder and removed. Furthermore, after the land had once become mantled with the æolian formation, it would have been protected from further wind erosion. The reason for the deposit of iron oxide over the granules of desert sand has not been fully explained. The most plausible explanation is that it results from the decay of iron-bearing minerals associated with the quartz. In the case of the red sands of the Arabian desert described by Phillips (see page 643 of this paper), the sand is apparently stagnant, and there occurs an exceptional amount of this oxide, very probably due to the better opportunity for residual action. With no iron-bearing minerals present in the Sylvania to be decomposed, it is not clear how any oxide could be formed or expected. Just beneath the till covering of the bed the formation is generally thus stained to a depth of a foot or more, but due to percolating water from the recent deposit.

So far as field data are available, the material making up the Sylvania formation seems to have come from the northwestward, and very probably was derived from the breaking down of the Saint Peter (Ordovician) sandstone of eastern Wisconsin,[73] either by wave or wind action, or both, and swept to the southeastward by prevailing northwest winds during mid-Monroan (Silurian) time. This deposit is a very pure (about 99 per cent) aggregation of rounded granules of crystalline quartz, very similar in appearance to the Sylvania, but of average coarser texture and containing a greater variety of original material (see figures 1 and 2, plate 47). Like the Sylvania, also, it is typically incoherent, readily crumbling in the fingers, and believed by Berkey to have been itself very largely an æolian formation.[74] Owing to this lack of binding material, the formation must have been readily disintegrated, and appears now in Wisconsin in fragmentary condition. To the basal sandstones of the Lake Superior region Berkey looks for the origin of the bulk of the Saint Peter material (page 243), being "washed out by the retreat of the sea and thereby assorted, then worked many times over by the wind in the absence of the sea, and thereby still more perfectly assorted, and finally, in the readvance of the sea, much of it was again worked over a last

[73] For a description of this formation the reports of the geological surveys of Wisconsin, Minnesota (vols. 1 and 2), Iowa (vol. 1), and Illinois (vols. 3 and 5) may be consulted. Also Owen's Geological Survey of Wisconsin, Iowa, and Minnesota, 1852, and Eleventh Annual Report of the U. S. Geological Survey, 1892.

[74] Berkey: Paleogeography of Saint Peter time. Bulletin of the Geological Society of America, vol. 17, 1906, p. 246.

time, thereby reaching its present remarkable condition of purity" (page 246). Derived from such a parent bed and inheriting such characteristics, the perfection of the æolian granule as typified by the Sylvania is not so surprising, in comparison with which the Sahara sand is in but a state of infancy. (Compare figures 3 and 4, plate 45; figures 1 and 2, plate 46, and those on plate 47).

In order to ascertain whether any evidence might be found in a study of the inclusions contained in the Sylvania and Saint Peter granules calculated to disprove, or render improbable the origin of the former from the latter, a half dozen samples of each formation were submitted to Prof. C. H. Smyth, Jr., of Princeton University; to Prof. C. P. Berkey, of Columbia University, and to Dr. A. C. Lane, of Tufts College, for microscopic study. Through their kindness we are able to append the following statements:

"I can find nothing in the way of inclusions that is distinctive, but merely the ordinary minerals and fluids of granitic and vein quartz. So far as I can see, there is nothing to show that the Sylvania is derived from the Saint Peter, while, on the other hand, there is no indication that it is not so derived. Thus, if you have other lines of evidence indicating such derivation, the inclusions in the quartz grains do not, so far as I can see, give any conflicting testimony.

"C. H. Smyth, Jr.

"Princeton, New Jersey, *June* 10, 1910."

"Before leaving home I mounted some of each sample of sand and looked them over with such care as I could. I must say that I can not see any difference in the two great sources in anything that could be regarded as an essential character. Both show the same types of sources—the quartz-bearing crystalline rocks—and both show fine sorting and rounding; also both are much inclined to show enlargement by addition of secondary quartz. I have not been able to undertake more elaborate comparisons. It seems to me to be almost a hopeless task to prove very much in this direction for these reasons.[75] Both formations' ultimate supply of materials must be traced back to the crystallines—the same or similar in origin, character, occurrence, distribution, and composition. If two grains side by side in the Sylvania were immediately derived—one from the Saint Peter and one from the crystallines direct—I don't see any very good way of proving which was which. If one were more round, it might be assumed to be the Saint Peter one, but even that I am somewhat

[75] It was not the thought of the writer that the origin of the Sylvania from the Saint Peter could be demonstrated from a microscopic examination of the grains of each formation, since, as pointed out by each of these investigators, they might have had a common but independent origin and similar history. With the field evidence, however, pointing to such origin, the writer was desirous of learning whether the granules themselves furnished any evidence that would render such an hypothesis untenable. From the three reports given, the reader will note that no such contradictory evidence has been found, and such an origin for the Sylvania becomes possible. The probability of such an origin is an entirely different matter.

what afraid might occasionally have to be reversed. I have very little doubt myself of the successive derivations of sand from previous sands—the Saint Peter from the Basal sands and the Sylvania from both—but I doubt whether it can be proven by any means yet at hand. I have been in hope that we might find a grain showing two stages of history in some such way as this—(*a*) rounding and deposition, (*b*) secondary enlargement, (*c*) erosion and re-wearing of the edges cutting down the angles of the secondary growth, (*d*) redeposition. In such a case one might be able to see the fact of there having been a second period of wear on the grain, and I would consider such a thing conclusive. But I haven't found anything even suggesting it.

"CHARLES P. BERKEY.

"KETCHUM, IDAHO, *July* 8, 1910."

"Great stress can not be laid on similarity of enclosures as to origin of sand, because a lack of similarity might be due to the introduction of some partial source, and, secondly, because similarity might be due to a common source. However, so far as the samples sent me are concerned, there is no reason why Sylvania might not be derived from the Saint Peter. In fact, the indications are that way so far as they are of value. Both are mainly quartz. In both (salt shaft base and Saint Paul, Minnesota) microcline or other feldspar *rarely* occurs. In the Sylvania there are rhombs of carbonate which are, however, I think, always on the outside. Quartz with hair-like needles of rutile are common in both. Lines of enclosures along planes, generally gas, apparently, but sometimes fluid, with occasionally gas bubbles (Sylvania, 7 miles north of Monroe, 7 feet down), also occur in both. Small enclosures which may be identified as apatite and zircon occur in both. Tourmaline occurs in brownish tinges, and some small, thin hexagonal folia, which may be biotite (Saint Paul, about 10 feet below Trenton; Fitchburg, Wisconsin; Rockwood, 20 feet down). In one grain from the Missouri Saint Peter there seemed to be a knee-shaped crystal of rutile in quartz which I did not see elsewhere, and one grain of the basal salt shaft was a crystal with much higher refraction than sharp quartz, crystalline in form and colorless, which I did not identify. It may possibly be celestite. There were, of course, unidentifiable enclosures, but I saw nothing in one set of sands characteristically different from the other set of sands, nor was there anything in the way of grain such as hornblende, epidote, monzonite, or similar materials which might serve as a characteristic difference.

"A. C. LANE.

"TUFTS COLLEGE, MASSACHUSETTS, *June* 2, 1910."

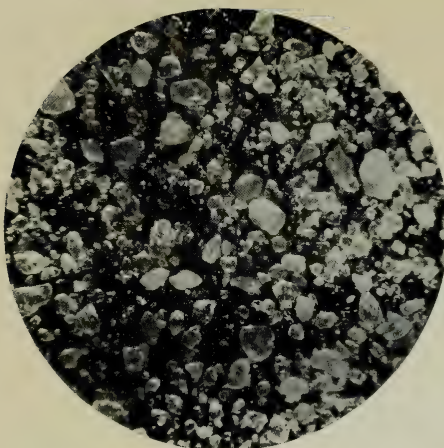
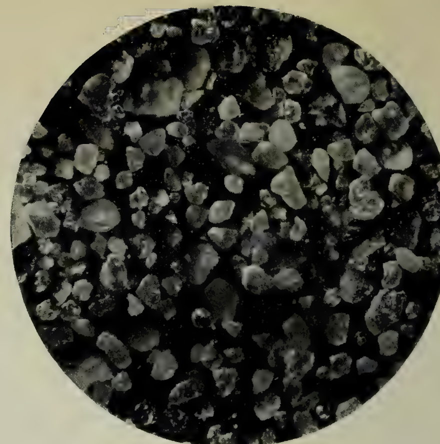


FIGURE 1



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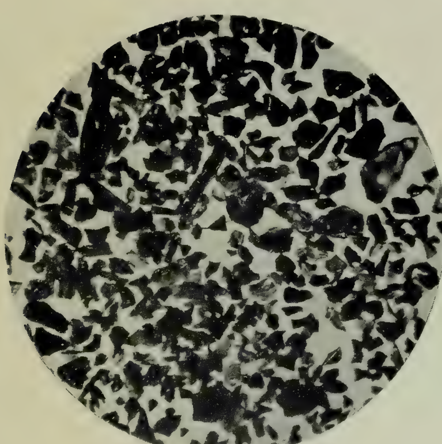

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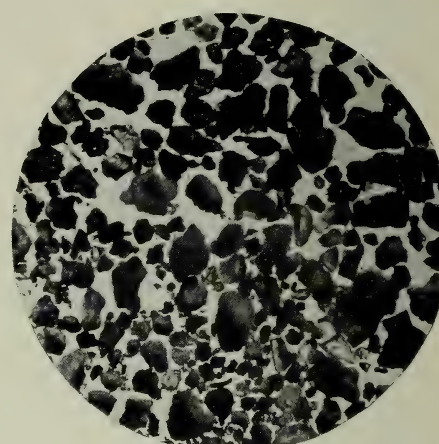

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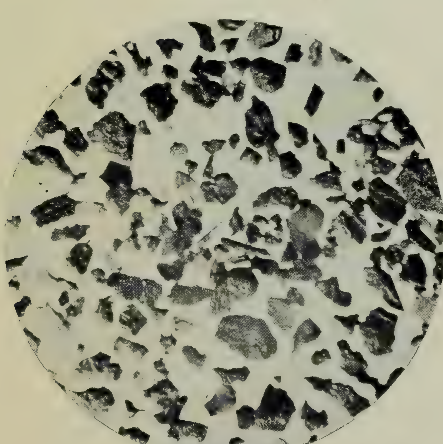

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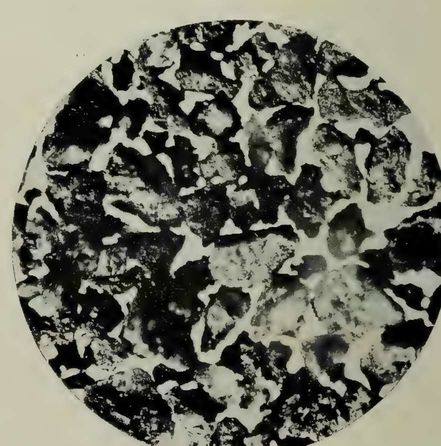


FIGURE 6

TYPES OF SAND GRAINS

Explanation of Plates

Plate 43.—Types of Sand Grains

Figure 1.—*Glacial Sand from the Mer-de-Glace, Switzerland.* (× 20½.)

Sharp, fresh, angular fragments, with but slight traces of weathering and very little of wear. Composition various, poorly assorted. Seen by reflected light. Collected by the author.

Figure 2.—*Sand washed from Wisconsin Till, Ypsilanti, Michigan.* (× 20½.)

Similar to figure 1, but showing evidence of both wear and weathering. Apparently an admixture of glacial, aqueous, residual, and possibly æolian types. Reflected light. Collected by the author.

Figure 3.—*Volcanic Sand of the angular Variety, showing no Erosion.* (× 14.6.)

Fragments glassy, vesicular, with flowage lines. Hawaii. Received from Dr. G. P. Merrill, U. S. National Museum. Viewed by transmitted and reflected light.

Figure 4.—*Volcanic Sand of the rounded Variety resulting from either Erosion or a plastic Condition of the Material.* (× 14.6.)

Slaggy and glassy. Mount Pelee eruption of 1902. Collected by Prof. T. A. Jaggar, Jr. Transmitted and reflected light.

Figure 5.—*Residual Sand from Diabase, Medford, Massachusetts.* (× 14.6.)

Granules angular and much weathered; rusted and more or less opaque. Detached crystals near center. Signs of erosion wanting. Supplied by U. S. Geological Survey. Reflected and transmitted light.

Figure 6.—*Residual Sand from Diabase, Brighton, Massachusetts.* (× 14.6.)

Similar to figure 5, but of coarser texture. Supplied by Michigan State Normal College. Reflected and transmitted light.

PLATE 44.—TYPES OF SAND GRAINS

FIGURE 1.—*Aqueous Sand, Mouth of the Tiber, Italy.* (× 20½.)

Granules assorted; fresh, angular, but with corners and edges rounded. Various composition. Collected by Prof. B. L. D'Ooge. By reflected light.

FIGURE 2.—*Aqueous Sand, Shore of Lake Huron, Kincardine, Ontario.* (× 20½.)

Very similar to figure 1. Collected by Prof. M. S. W. Jefferson. Reflected light.

FIGURE 3.—*Aqueous Sand, Atlantic Coast, Marthas Vineyard, Massachusetts.* (× 20½.)

Granules fresh and subangular, but more rounded than figures 1 and 2. Collected by Prof. M. S. W. Jefferson. Reflected light.

FIGURE 4.—*Aqueous Sand, Atlantic Coast, West Palm Beach, Florida.* (× 20½.)

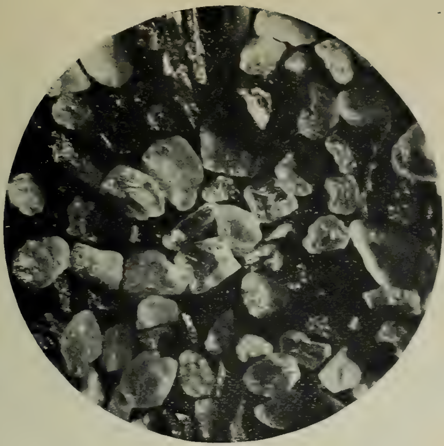
Granules well assorted; pure, crystalline quartz; much worn, but still subangular. Extreme type of aqueous sand. Supplied by E. E. Free, U. S. Bureau of Agriculture. Reflected light.

FIGURE 5.—*Aqueous Sand, shore of Lake Michigan, Holland, Michigan.* (× 20½.)

Coarse, fresh, well assorted as to size; varied composition. All granules show erosion, the two well rounded ones below the center having probably been exposed to wind action as well as water. Collected by Prof. M. S. W. Jefferson. Reflected light.

FIGURE 6.—*Æolo-aqueous Subtype of Sand, from Dune, Holland, Michigan (near Figure* 5 *Sample).* (× 20½.)

An aqueous type of sand being modified by the wind. Note the character of the bean-shaped granule just southeast of the center. Collected by Prof. M. S. W. Jefferson. Reflected light.



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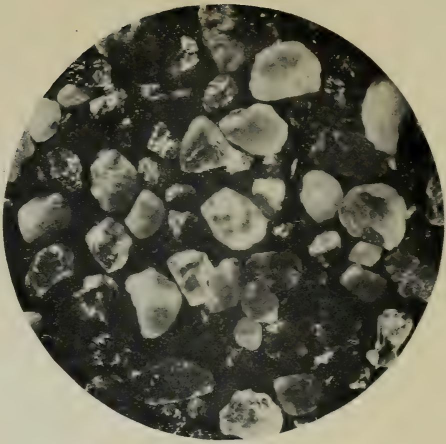

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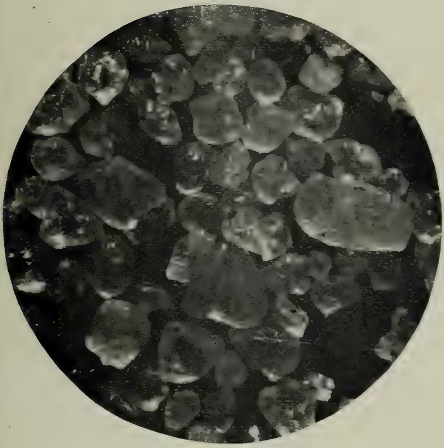

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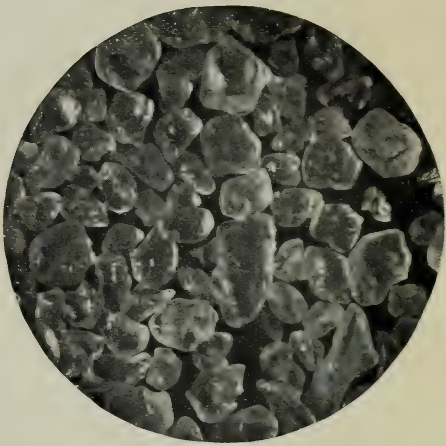

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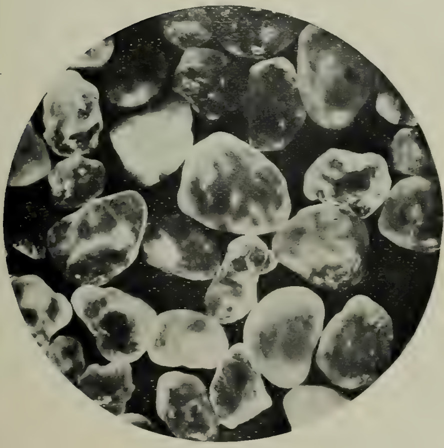

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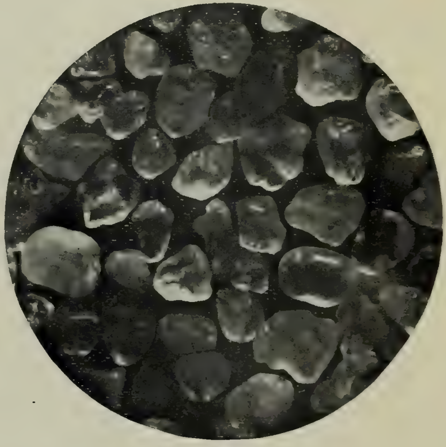


FIGURE 6

TYPES OF SAND GRAINS

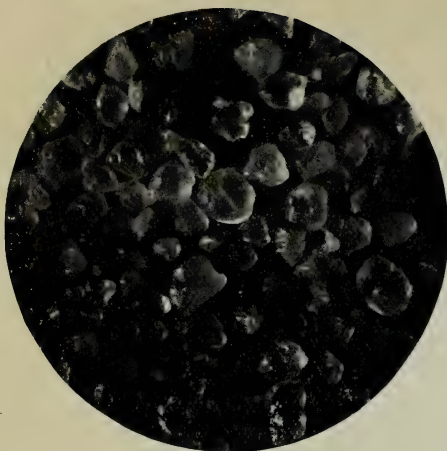
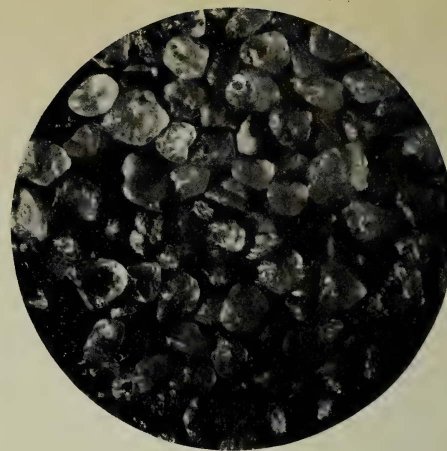


FIGURE 1



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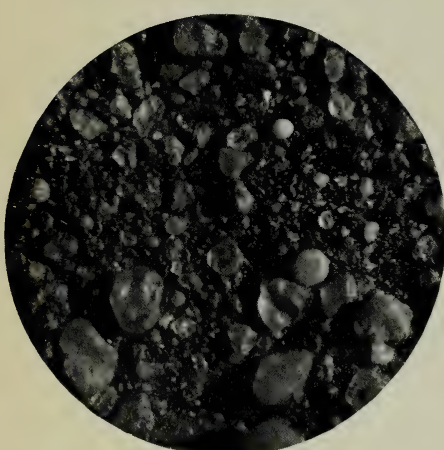

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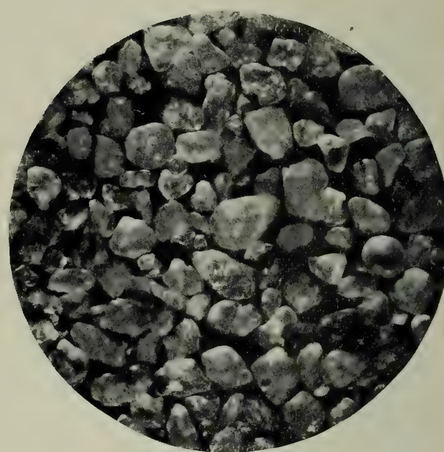

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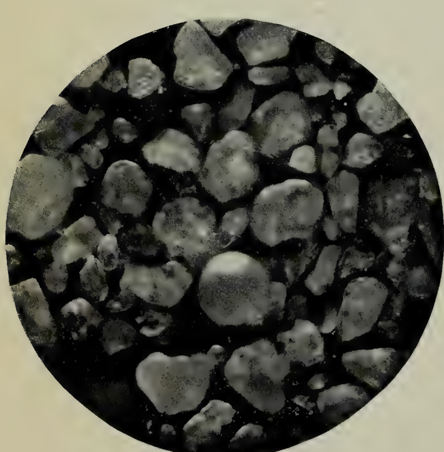

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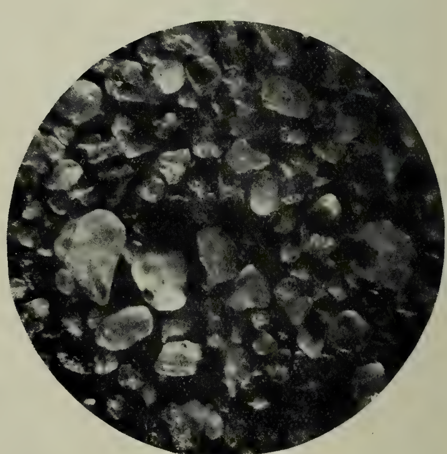


FIGURE 6

TYPES OF SAND GRAINS

PLATE 45.—TYPES OF SAND GRAINS

FIGURE 1.—*Æolo-aqueous Subtype of Sand; Dune, Lake Michigan Shore, Muskegon, Michigan.* (× 20½.)

Rather fine, well assorted, quartz predominant; wind action indicated by tendency toward the subspherical, away from the subangular outline. Collected by Prof. M. S. W. Jefferson. Reflected light.

FIGURE 2.—*Æolo-aqueous Subtype of Sand; Dune, Pacific Coast, near San Francisco, California.* (× 20½.)

Closely related to figure 1; approaching the æolian type; indicated by well rounded outlines. Supplied by the U. S. Geological Survey. Reflected light.

FIGURE 3.—*Æolo-residual Subtype of Sand, from near Cairo, Egypt.* (× 20½.)

Poorly assorted as to size; quartz predominant. The coarser granules are smoothed and rounded, three having been reduced to almost perfect spheres. The finer material has been less affected and remains subangular to angular. Collected by Prof. B. L. D'Ooge. Reflected light.

FIGURE 4.—*Æolo-residual Subtype of Sand, from Gizeh, Egypt.* (× 20½.)

Well assorted; quartz predominant. Granules subangular to subspherical, with frosted and pitted surfaces. Collected by Mrs. Julia A. Sherman. Reflected light.

FIGURES 5 AND 6.—*Desert Sand from near Albuquerque, New Mexico.*

Showing general similarity with figure 4. If derived by wind action on a residual sand the subtype is æolo-residual. It is not improbable that some is also æolo-aqueous. Collected by Dr. A. C. Lane. Reflected light.

PLATE 46.—TYPES OF SAND GRAINS

FIGURE 1.—*Æolo-residual Subtype of Sand, Libyan Desert.* (× 20½.)

Texture medium to fine; mainly quartz. The finer material is an admixture of well rounded and angular particles. The coarser granules are subangular to subspherical, and show the dulled surface and characteristic pitting of figure 2. Collected by Dr. Johannes Walther. Reflected light.

FIGURE 2.—*The coarser Granules mechanically removed from Sample from which Figure* 1 *was taken.* (× 20½.)

The prominent grains are about 1 millimeter in diameter and have their upper surfaces focused on in order to show the characteristic dull surface (referred to as "frosted") and the pitting, neither of which are seen in typical sand of any other variety.

FIGURE 3.—*Aqueo-organic Subtype of Sand from Rovigno, Adriatic Sea.* (× 14.6.)

Shells of foraminifera, mollusca, and miscellaneous calcareous fragments from other organisms. Partially broken and rounded by water action, both mechanical and chemical. Supplied by the University of Berlin. Reflected light.

FIGURE 4.—*Oölitic Sand, organic Type; Garfield Landing, Great Salt Lake, Utah.* (× 14.6.)

There are shown the spherical, rod-like and irregular, or "tubercular" types of granules, with numerous connecting forms. Collected by Prof. I. C. Russell. Reflected light.

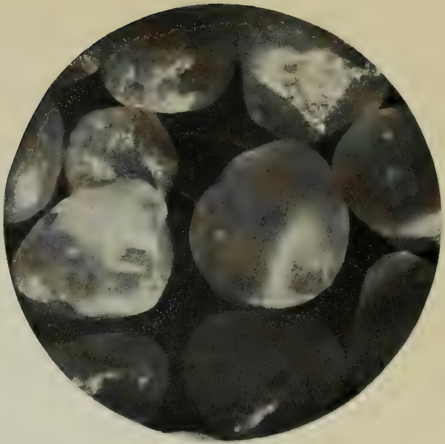
FIGURE 5.—*Gypsum Sand, "concentration Type," near Alamogordo, New Mexico.* (× 14.6.)

Granules well assorted, almost entirely white gypsum, and rounded except when freshly cleaved, when straight edges and more or less sharp angles are seen. Collected by Ray I. Clink. Reflected light.

FIGURE 6.—*Secondarily enlarged pure Quartz Sand from the Sylvania Formation; Pit of National Silica Company, Monroe County, Michigan.* (× 20½.)

Classified as "concentro-æolian" subtype; a rounded æolian granule with a doubly terminated quartz prism formed about it. Collected by the author. Reflected light.

FIGURE 1



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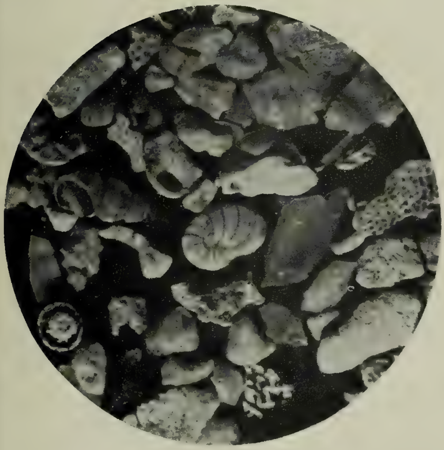

FIGURE 3

FIGURE 4

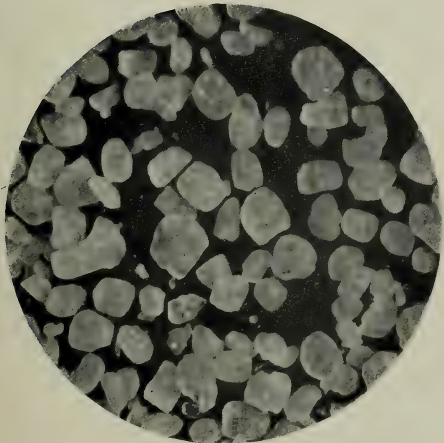

FIGURE 5

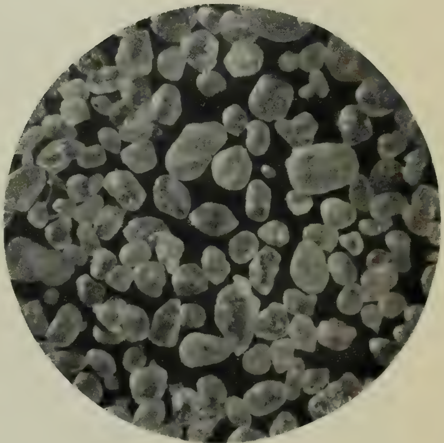

FIGURE 6

TYPES OF SAND GRAINS

Plate 47.—Types of Sand Grains

Figure 1.—*Saint Peter Sand Granules, Ordovician Age; Saint Paul, Minnesota.* (× 20½.)

Well assorted, pure quartz; æolian type, probably derived from water-shaped granules. Supplied by Prof. C. P. Berkey. Reflected light.

Figure 2.—*Same as Figure 1, but of average coarser Texture; Minneapolis, Minnesota.* (× 20½.)

More of the subangular variety of granules shown, and some indicating secondary enlargement. Supplied by Prof. C. P. Berkey. Reflected light.

Figure 3.—*Sylvania Sand Granules, Silurian Age; Pit (near Top) National Silica Company, Monroe County, Michigan.* (× 20½.)

Well assorted and rounded, pure quartz; æolian type. The finer specks between the granules represent small rhombohedrons of dolomite secondarily introduced. Perfect rounding in granules 1/10 millimeter and less in diameter. Collected by the author. Reflected light. The Saint Peter is regarded as the most probable source of the Sylvania.

Figure 4.—*Sylvania Sand, coarser average Texture than Figure 3, Detroit Salt Shaft, near Top.* (× 20½.)

Finer specks of dolomite between granules, and not original. Collected by the author. Reflected light.

Figure 5.—*Sylvania Granules, from small concretionary-like Pellets, disintegrated by use of Acid; Pit National Silica Company, Monroe County, Michigan.* (× 20½.)

In such pellets the assorting of the granules is least perfect. Collected by the author. Reflected light.

Figure 6.—*Sylvania Granules, from Pit of the American Silica Company, Rockwood, Michigan (4 Feet from Top).* (× 20½.)

This assorting was entirely natural, and, combined with the remarkable rounding, is the most perfect specimen of æolian sand seen by the author. It may be regarded as the extreme toward which desert sands are slowly working. The granules are all quartz and coarser than the average Sylvania. Collected by the author. Reflected light.

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ROCK STREAMS OF VETA PEAK, COLORADO[1]

BY HORACE B. PATTON

(*Presented before the Society December 29, 1909*)

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DEFINITION AND PREVIOUS DESCRIPTIONS

The name "rock stream" as a geologic term has been in use but a very short time, having been first employed by Whitman Cross and Ernest Howe in connection with certain very remarkable accumulations of rock debris described by them in the Silverton Folio (Colorado),[2] which was published in 1905. These rock-debris masses were found only on the floors of glacial cirques at the head of the valleys and presented features strikingly different from ordinary talus slopes. To quote the above named authors:

"The most striking of these masses, and those to which attention was first directed, closely resemble debris-covered glaciers at the heads of the basins or cirques in which they occur. The surfaces are hummocky and uneven, depressions that strangely simulate crevasses frequently occur, and concentric ridges and depressions are often seen at the end of the accumulations, which are abrupt and have steep faces often rising 100 feet or more above the floor

[1] Manuscript received by the Secretary of the Society October 29, 1910.
[2] U. S. Geological Survey, Geologic Atlas, Silverton Folio (No. 120), p. 25.

of the cirque. This may be clean or may be covered by a thin, disordered sheet of bowlders and soil. . . . All of the accumulations of the sort just described impress one with a sense of motion, looking as if they had flowed as do viscous masses, and were still advancing from the head walls of the cirques downward. So noticeable was this that in the field they were spoken of as 'rock-glaciers' and upon the map receive the name 'rock streams.'"

The striking differences between these rock streams and ordinary talus slopes on the one hand and landslides on the other hand were plainly brought out by the above named authors. Although some of the less marked rock streams were not so clearly distinct from talus slopes, the larger ones were considered to be of distinctly glacial origin. At the same time it was recognized that they could not be accounted for by the ordinary action of alpine glaciers. In order to account for the remarkable quantity of coarse material composing them and for the fact that, in their opinion, the material must have been carried along by glacial ice, it was suggested that, during the period of glacial retreat, after most of the ice in the high glacial cirques had disappeared, and only local glaciers of very small extent remained, landslides occurred at the steep-walled heads of the glacial cirques, and the material thus precipitated upon the diminishing glaciers was carried downward by the slowly moving ice and left eventually in stream or moraine-like masses.

Subsequent investigation by the same authors has revealed the presence of many more such rock streams in other portions of the San Juan Mountains, and mention of them is made in the Ouray and Needle Mountain folios of the U. S. Geological Survey.

Observations made by the writer in different parts of Colorado, but more especially the discovery of some very beautiful rock streams on Veta Peak during the summer of 1909, convinced him that such phenomena are not as rare as might be supposed from the fact that they have only recently been recognized as a distinct topographic feature. It was also very clear from the conditions surrounding the Veta Peak rock streams that glacial action is by no means necessary for their development.

That the above-named authors have had reason to change their former views as to the origin of the San Juan rock streams was made known to the writer while he was engaged in the preparation of this paper by the arrival of the advance copy of Mr. Ernest Howe's paper, "Landslides in the San Juan Mountains, Colorado."[3] In this beautifully illustrated and extremely interesting paper there is described at some length the various landslides in the San Juan Mountains and included in these phe-

[3] U. S. Geological Survey, Professional Paper No. 67.

nomena are the rock streams. He refers at some length to the descriptions of the great landslides at Elm, in the Alps, and at Frank, on the line of the Canadian Pacific Railway, draws comparisons between them and the San Juan rock streams, and concludes as follows:

"The striking similarity that the Frank landslide bears to so many of the San Juan rock-streams can leave the origin of these latter deposits open to no doubt. Although it is not impossible that ice may have played an important part in their formation, the writer believes that they are strictly landslides and owe their present form entirely to the nature of their fall and to the character or physical condition of the rocks involved in the fall."

Description of Veta Peak

Veta Peak, also called Veta Mountain, lies in Huerfano County, in the southern part of Colorado, about 12 miles northwest of the town of La Veta. To those traveling over the Denver and Rio Grande Railway from Pueblo into the San Luis Valley via La Veta and the Veta Pass this mountain appears as a very conspicuous, steep-sided cone. The old narrow-gauge line of the Denver and Rio Grande Railway, now abandoned, formerly followed up the South Veta Creek to the very base of Veta Peak. The present broad-gauge line keeps farther to the south, but from La Veta up to the pass affords a splendid view of this very conspicuous mountain. The mountain is really not a single conical peak, as it appears to be when seen from the southeast, but a more or less irregular ridge having a general northwesterly trend and divided into two distinct summits by a deeply cut notch. These two summits are called respectively North Veta Peak and South Veta Peak. These peaks consist entirely of igneous rocks in the form of great dikes cutting Carboniferous rocks. The South Veta Peak, on the west side of which lie the rock streams under consideration, is composed of a light gray, remarkably uniform porphyry that is entirely free from visible phenocrysts. This rock is of a light gray color and weathers whitish. It has a dull stony luster and breaks into flattish slabs with a slight tendency to conchoidal fractures. It is medium to fine grained, but never flint-like in texture. It has been called a granite felsophyre by R. C. Hills,[4] and shows a strong tendency to break up into angular fragments under the influence of frost. Although the porphyry mass that forms the mountain rises a thousand feet or more above the sedimentary base, nowhere is the porphyry to be seen forming a solid ledge except where it has been recently exposed by a landslide. The elevation of the mountain

[4] U. S. Geological Survey, Geologic Atlas, Walsenburg Folio (No. 68), p. 4.

is about 11,600 feet. At the west foot of the ridge flows a small stream, the South Veta Creek. The ridge is extremely precipitous on this side and the creek has cut a deep valley that lies some 2,500 feet below the crest of the ridge.

Veta Peak stands quite isolated from the main range of the Sangre de Cristo divide, over which the railway passes to the west. It is absolutely devoid of vegetation on the higher parts, although a heavy growth of timber is to be seen covering Carboniferous rocks lower down the slope.

On the western slope of this ridgelike peak occur two very pronounced rock streams that started as landslides from the crest of the ridge and ended below in tonguelike extensions that present in the most marked fashion evidences of streamlike motion. While these streams started from contiguous portions of the ridge they terminated in streams whose lower ends are about a mile apart.

These rock streams were investigated by the writer in the fall of 1909. At first he was not aware that there were two streams, so that almost the entire available time was put in a study of the north rock stream, as this was the first to be discovered. It was not until the day was far spent and no time remained for a detailed study that the second or southern rock stream was discovered. For this reason the south rock stream must be allowed to pass with but brief mention and the detailed description be limited to the north rock stream.

Description of the North Rock Stream

General Characteristics

This rock stream differs very materially from all those described by Cross and Howe, first, in that the lower and more pronounced portion of the stream is not found on an open and flat floor, but is confined to the bottom of a narrow and sharply defined valley; and, second, in that it is a stream formed by the union of two distinct tributaries. Nothing can be more striking or, to a geologist, more startling than a first view of this rock stream as seen from a high level on the west side of the valley of South Veta Creek. The valley runs at this point approximately north and south and parallel to the crest of the peak. The rock stream occupies the bottom of a lateral valley that runs diagonally down from the north end of the peak at a point close to the notch. The sides of the lateral valley are composed of dark red shales and sandstones of Carboniferous age, more or less obscured in places by a scanty growth of pines and bushes. But the color of these red rocks stands out in sharp contrast with the comparatively white color of the rock stream in the bottom of the valley—a contrast made all the more effective because of the complete lack of vegetation on the rock stream itself. Not even the presence of glacial ice in the Alps extending far down below the snow line and into the forested regions of the lower valleys is more striking in the way of contrast than this tongue of white porphyry fragments running far down into the region of red Carboniferous shales. In fact, the resemblance to a glacier is most surprising, a resemblance that is heightened by a study of the detailed structure of the rock stream.

In plate 48, figure 1, is seen a view of this rock stream as taken from the west side of the main valley and at a level some 500 feet above the base of the rock stream. To the left of the notch is North Veta Peak and to the right of the same is South Veta Peak. In plate 48, figure 2, is seen a nearer view of the same rock stream taken from the wooded slope to the north of the stream and opposite a point about 1,200 feet above the lower end of the stream. In each view the source of the material can be seen on the ridge of the peak. The landslide that developed into a rock stream in the lower portion started at the crest of the ridge. The rock broke away in a practically continuous mass between the notch and *b*, a distance of perhaps three-quarters of a mile. Beyond *b* to the right the break continued, but the material derived from the part of the mountain covered by the last two gulches to the right of *b*, as seen best in figure 2, flowed down farther to the south and formed the south rock stream.

The north rock stream may be divided into three parts—the north branch, the south branch, and the main stream below the junction. The north branch has about the same width as the south branch, but is much longer and contains much more material. Below the junction it forms perhaps nine-tenths, certainly three-quarters, of the combined stream. The junction of the two branches is best seen in plate 49, figure 1. In this plate the rock material appears much darker than it should, owing in part to under exposure of the photographic plate and in part to contrast with the snow.

CHARACTER OF THE MATERIALS

The materials composing the two branches is the same, namely, the whitish colored porphyry composing the summit of the mountain. Although the rock stream passes down between banks of red shale and sandstone for a distance of 1,700 feet or more, not one particle of any other kind of rock than porphyry is to be seen. Furthermore, the porphyry fragments present a very unusual uniformity, in that there appears to be no appreciable difference in texture or composition or outward appearance in different portions of the stream. A striking feature is the comparative uniformity in the size of the rock fragments. In the greater part of the stream there appears to be absolutely no fine material such as clay or sand, but simply clean, angular fragments of rock without a particle of finer cementing material. Equally noticeable is the absence of very large fragments. In only one case was a rock fragment of over 6 feet noticed. As will be noted later, the size of the fragments may vary considerably in different portions of the stream, but within certain well defined sections the size is very uniform, say from 1 to 2 feet in diameter. See plate 51, figure 1. On the other hand, certain portions of the rock stream do contain considerable sand and clay. This is particularly noticeable in the southern branch. Such portions are also more or less covered with vegetation, whereas the parts free from fine materials contain no vegetation whatever.

SIZE AND ELEVATION

Elevations were taken by aneroid barometer and are not perfectly reliable, as no efficient check on the readings could be made. The elevation of the ridge of South Veta Peak at the point where the landslide started is something over 11,000 feet, probably about 11,200 feet, above sealevel. The bottom of the valley of South Veta Creek where it is joined by the side valley in which the rock stream lies is approximately 8,800 feet high. The lowest point of the rock stream is some 200 feet vertically above this junction of the valleys and is distant about 2,000 feet therefrom. The total drop, therefore, from the crest to the bottom of the rock stream is 2,200 feet. The total distance traveled by the rock fragments as measured between these two points is upward of one mile. The rock stream proper measured from the base of the steep declivity, seen in plate 48, figures 1 and 2, to the left of *a*, is 4,500 feet. In width the two branches are each about 1,000 feet a short distance above the junction. Below the junction the combined stream measures about 500 feet wide. The depth can not be determined, but, judging from the average slope of the valley bottom below the rock stream and from such measurements as could be taken, it was estimated that the depth of the stream at a point some 300 feet from the lower end is not less than 130 feet.

SURFACE FEATURES

Although the surface of the rock stream shows in the main a relatively uniform slope down stream, the average for the north branch being about

8 degrees, at each side and at the end the mass of rock debris suddenly pitches off at an angle of 35 degrees, so that the fragments are in a state of unstable equilibrium and are easily set moving if one attempts to climb over them. At the sides, therefore, there is a marked trough formed between the rock stream and the rock formations in place, a feature very suggestive of the lateral moraines of alpine glaciers.

The concentric billows and irregular hummocks that are so marked a feature of many of the rock streams of the San Juan Mountains are not very noticeable in this rock stream. In the central portion of the north branch, where the stream suddenly changes to a much greater pitch, there are several rolls or billows suggestive of the billows of a cataract in a river. Three of these may be seen in plate 48, figure 2, at the lower edge just to the left of the middle of the picture. The hollows or flats are here indicated by the three parallel snow patches. In reality they are much more pronounced than is indicated by the picture. In the upper portions of rock streams, near the foot of the steeper part of the landslide, hummocky billows and flats so characteristic of landslide areas are much in evidence, but not so in the more characteristic rock stream portions where the evidences of motion are most marked.

Instead of hummocks and billows this stream is characterized by the presence of parallel ridges and troughs that conform to the direction of the rock stream and that persist for many hundreds of feet. The ridges may be, and usually are, quite flat, while the troughs are much sharper and narrower. By means of these troughs and ridges the direction of movement may be traced as readily as my means of medial moraines in the case of actual glaciers. Plate 49, figure 1, shows this feature where it is most pronounced at the junction of the two branches. Plate 49, figure 2, shows the ridges somewhat flatter. This view is taken from the south side of the stream below the junction of the two branches. It shows practically the whole of the stream where it is narrowest, 500 feet, and gives an idea of the uniform slope of the rock stream. The wooded slope beyond the rock stream is composed of Carboniferous rocks.

As will be seen in the description of the north branch, this rock stream conforms, as do glaciers, to the larger irregularities of the valley, turning with the valley; but, like glaciers again, it is unable to conform to the lesser irregularities of the surface. A striking instance of this is seen in the damming up, so to speak, of a flat side valley on the north side of the north branch several hundred feet above the junction of the two branches. At this point the rock stream, like the lateral moraine of a glacier, passes uninterruptedly across the mouth of this side valley at a level of 50 feet above the level of the side valley. This is shown in plate 50, figure 1. This view is taken from the bottom of the side valley looking up at the rock stream whose direction of motion is at right angles to the line of view.

DETAILS OF STRUCTURE

Reference has already been made to the ridges and intervening troughs. The former are often merely long, narrow flats raised 4 or 5 feet above each other, with no marked trench or trough between them. The rocks composing these flat ridges usually have a distinct and often very marked horizontal arrangement, the individual slabs lying flat. On the other hand, in the troughs, especially where sharp and narrow, the rocks show a strong tendency to stand on edge, with their long diameters parallel to the direction of flow. In plate 50, figure 2, is shown a mass of flattish rock fragments measuring from 1 to 3 feet in greatest length and turned on edge. This view is taken at the bottom of a pronounced trough. The contrast between the flat-lying slabs of the ridges and those turned on edge is also brought out clearly in plate 52, figure 2. In this case there is no real trough in evidence, but merely a higher bench of flat-lying slabs and a parallel running lower bench in which the fragments are mostly turned up on edge.

It is also to be noted that where two flat ridges or parallel benches occur on different levels there is usually a marked difference in the average size of the rock fragments composing the two benches. This difference in size persists throughout the whole length of the ridge. It can hardly be explained except on the assumption that the material of the two ridges comes from different sources somewhat after the manner of two lateral moraines uniting to form a medial moraine. This contrast in size of the constituent fragments may be seen in plate 51, figure 1; likewise in plate 49, figure 2.

The North Branch

As above stated, this branch forms the major part of the whole rock stream. It not only is much longer than the south branch, but after the two streams unite the material from the north branch forms perhaps nine-tenths of the entire mass and continues also farther down stream. Throughout its entire length it is almost entirely free from fine material, and also free from vegetation. This rock stream started at the point *a* in plate 48, figures 1 and 2, in the shape of a regular landslide with an initial direction of north 60 degrees west. Descending with terrific velocity for some 1,200 or 1,500 feet vertically, the rockmass met with obstructions at the foot of the declivity which caused most of it to turn to the left through an angle of 80 degrees and to take a direction of south 40 degrees. From the point where the turning begins at the bottom of the steep declivity downward the rock stream features become increasingly marked. At the upper end they are hardly noticeable. From this point of first turning downward the rock stream undulates with the course of the valley, gradually turning still more to the left toward the bottom, till at the very end the direction of motion is such that the stream from its source at the top of the ridge to the lower end of the rock stream has turned through an angle of 110 degrees. Except for the first great plunge, this great mass of rock detritus has evidently flowed down the valley at a gentle slope of only 8 degrees, practically as though it were a liquid. And yet there is no evidence of any appreciable amount of fine material like mud that could have formed a lubricant. Starting as it did, there could hardly have been much water accompanying the rock debris, so that the moving mass must have consisted essentially of rock debris and air. As in the case of the Elm and Frank landslides mentioned above, the mass of rock fragments, moving at great velocity, and with no lubricating material except air and a little water, acts essentially like a liquid. In rubbing forcibly against each other the fragments would naturally be broken finer and finer and become more or less chipped. In fact, chipping of the larger fragments, as though with a hammer, is quite a common feature.

At the foot of the steep declivity where this north rock stream started, the rock material is accumulated in a series of parallel running ridges of considerable size. These ridges lie athwart the course of the descending landslide and are perhaps in part responsible for the deflecting of the rock stream to the left. It would seem that the landslide, being suddenly checked at the bottom of the declivity, piled up in ridgelike rock billows, and thus formed an obstruction that turned the course of the rest of the stream into the side valley, down which it proceeded to flow until its force was spent. In plate 48, figure 2, the scar left by the landslide at the head of this rock stream is very plainly shown to the left and below the letter *a*.

The South Branch

The south branch is comparatively broad and short and does not present such marked evidences of flowage, except at the lower end, as is seen in the north branch. The greater part of the area covered by this rock stream is more of the nature of ordinary landslides, with hummocky billows and hollows and a more or less level shelf marking the upper limit of the displaced mass. It also contains much more fine material and is more or less wooded. At the lower limit, however, this rock slide develops well defined rock stream features. It comes into the valley from the south side, making a graceful curve where it joins the larger north stream and follows down the left or south side of the valley, being quite distinct from and yet parallel with the stream from the north branch, until it finally ends 200 or 300 feet sooner than the north stream. In plate 48, figures 1 and 2, the source of the material of the south branch may be seen in the landslide that came down between the points marked by the letters *a* and *b*. Likewise in plate 51, figure 2, may be seen to the left of the letter *a* the scar of the landslide at the head of the north branch, and to the right of *a* the source of part of the south branch. This plate also shows the parallel ridges and troughs of the south branch with their curving lines just as they unite with the north branch. The trenches here shown are not to any degree due to water erosion, but purely to the motion of the rock stream itself.

In plate 52, figure 1, is to be seen the continuation of the above described plate 51, figure 2, taken some 200 or 300 feet lower down stream. The left part of the view shows a part of the north branch, the material of which lies at a slightly higher level. The lower lying portion to the right and in the center of the view represents the south branch flowing in on a curve from the right. Finally plate 52, figure 2, shows the same two flows taken still farther down stream. The rock material from the north branch continues still at a higher level and forms a bench of flat lying fragments, while the material from the south branch stands at a lower level and has its individual fragments turned on edge. This difference of level in the two branches continues to the end of the stream. Here again we see a marked resemblance between this rock stream and a glacier. In each case the materials from different sources and from different tributaries travel down the stream without mingling. If it were not for the fact that the rock material of the two tributaries is exactly alike in appearance, this feature would be much more marked than it is.

It is an interesting fact that where the two streams come together and are apparently squeezed into a narrow space between the steep sides of the valley, there the evidences of motion are strongest, and there, too, the rock fragments show most marked tendency to stand on edge.

Rock Streams and glacial Action

Rock streams as described by Cross and Howe in the San Juan Mountains of Colorado are limited to the very high mountain regions above the level of growing timber and at the heads of glaciated valleys. Their resemblance to glacial deposits and their association with glaciated areas naturally suggested some genetic connection with glaciers. But in case of the Veta Peak rock streams glacial action is entirely out of the question. In the first place, no glaciated valleys are found in Colorado at an altitude of only 9,000 feet. In the second place, even where glaciation has occurred in Colorado at altitudes of 10,000 to 11,000 feet, this has happened only in regions of extensive mountain masses. The elevation of Veta Peak, about 11,600 feet, is quite insufficient to have caused the starting of a glacier, even though the peak were located in close proximity to extensive mountains of greater size and extent. Still more is it impossible for glaciers to originate on an isolated peak far away from the high mountain ranges and on the edge of the plains. No glaciated areas occur within 10 or 15 miles of Veta Peak.

It is evident, therefore, that glacial action is in no way necessary for the production of rock streams of the most pronounced type. That rock streams are so common in the high mountain regions of the San Juan is doubtless due to the erosive agencies of glacial ice which have cut back the heads of the valleys into great steep walled amphitheaters and have thus produced conditions unusually favorable for landslides. It would seem, therefore, that rock streams may occur wherever conditions are such as to produce landslides of great mass and of great velocity. That such must have occurred in many other places is more than likely, but, as suggested by Mr. Howe, in most climates vegetation would quickly cover and obscure all evidences of ancient rock streams.

Just why Veta Peak should have been so favorable for the production of rock streams of evidently very recent origin is not quite clear. To be sure, the very steep mountain slope to the west of the peak was essential, but other mountain slopes of equal steepness have failed to account for like results. It would seem that a uniform igneous rock like that composing the summit of this peak, however readily it might break up under the action of frost, would hardly be likely to be precipitated in huge masses. From observations made by the writer in other parts of Colorado, he is convinced that rock streams with marked evidence of streamlike motion are by no means rare phenomena, and there is no reason to suppose that such phenomena are limited by any particular geographic bounds.

It may be noted, in conclusion, that rock detritus is quite capable of assuming parallel lines of flow without the interposition of either glacial action or of landslides. The writer has very often observed in high mountain regions in the Rockies that rock detritus very often arranges itself in parallel running ridges and troughs and that in such cases the trend of the ridges is invariably down hill, and that the rock fragments show a strong tendency to stand on edge. This occurs in places where glacial action as well as landslides are out of the question, but where snow-drifts lie till late in the summer. In such cases the only explanation that has occurred to the writer is that the arrangement is due to a slow creep of the rock fragments caused by the snow melting by day and freezing by night.

Description of Plates

Plate 48—Veta Peak, Colorado, and the North Rock Stream

Figure 1.—*General View of the north Rock Stream, looking East.*

The view is taken from a point about 500 feet above the level of the lower end of the rock stream. In the distance is the ridge of North Veta Peak to the left and of South Veta Peak to the right, with the notch between. At *a* is the top of the landslide that developed into the rock stream. The south branch of the rock stream started between *a* and *b*. The sparsely wooded hill in the foreground is composed of red shales and standstones of Carboniferous age.

Figure 2.—*Nearer View of the Source of the Rock Streams.*

These streams started as two landslides, one at *a* and the other between *a* and *b*. In the foreground to the left is a portion of the north branch, showing steplike rock billows.

Plate 49—The North Rock Stream

Figure 1.—*View of the middle Portion of the Rock Stream.*

The view is taken at the point where the north branch and the south branch unite, showing the longitudinal ridges and troughs.

Figure 2.—*View looking North across the Rock Stream.*

The view is taken at the narrowest part of the stream below the junction of the two branches. The wooded slope beyond the stream is Carboniferous. The view also shows several flat ridges and intervening troughs.

Plate 50—The North Rock Stream

Figure 1.—*View looking up at the Rock Stream.*

The view is taken from the bottom of a flat side valley that is dammed up by the rock stream. The direction of flow is at right angles to the line of vision.

Figure 2.—*Detail of the Rock Stream.*

The view shows the flat and uniform sized rock fragments standing on edge in the bottom of one of the troughs.

Plate 51—The North Rock Stream

Figure 1.—*Detail of Rock Stream.*

The view shows the trough between two flat ridges; also the uniformity in size of the fragments and the difference in average size of the fragments composing the two ridges.

Figure 2.—*View of Part of the South Branch.*

The view is taken at the point where the stream joins the north branch. It also shows the landslide scars at the head of the north branch to the left of *a* and of the south branch to the right of *a*, as well as the marked ridges and troughs and the curving lines of flow.

Plate 52—The North Rock Stream

Figure 1.—*View taken about* 200 *Feet below that shown on Plate* 51, *Figure* 2.

It shows portions of the north and of the south branch where they flowed along side by side.

Figure 2.—*View of the same Portions of the north and south Branches as shown on Plate* 52, *Figure* 1.

The view is taken still farther down stream. It also shows the difference of the level of the two streams and of the position of the rock fragments in each.

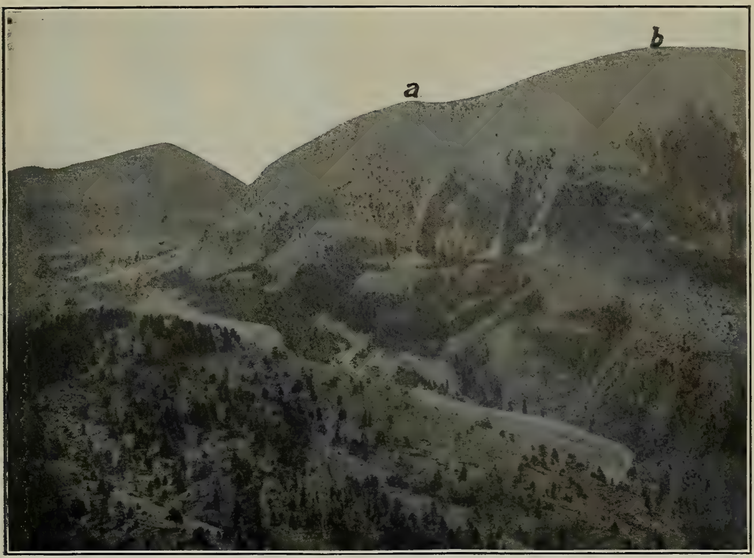

FIGURE 1.—GENERAL VIEW OF THE NORTH ROCK STREAM, LOOKING EAST

FIGURE 2.—NEARER VIEW OF THE SOURCE OF THE ROCK STREAMS

VETA PEAK, COLORADO, AND THE NORTH ROCK STREAM

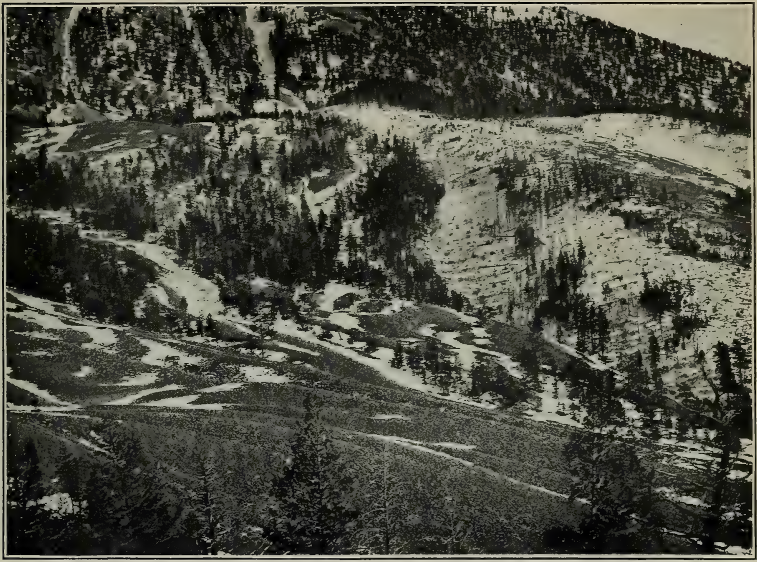

FIGURE 1.—VIEW OF THE MIDDLE PORTION OF THE ROCK STREAM

FIGURE 2.—VIEW LOOKING NORTH ACROSS THE ROCK STREAM

THE NORTH ROCK STREAM

FIGURE 1.—VIEW OF THE ROCK STREAM FROM A SIDE VALLEY

FIGURE 2.—DETAIL OF THE ROCK STREAM

THE NORTH ROCK STREAM

FIGURE 1.—DETAIL OF THE ROCK STREAM

FIGURE 2.—VIEW OF PART OF THE SOUTH BRANCH

THE NORTH ROCK STREAM

FIGURE 1.—VIEW BELOW THE JUNCTION OF THE NORTH AND SOUTH BRANCHES

FIGURE 2.—VIEW BELOW THE JUNCTION OF THE NORTH AND SOUTH BRANCHES

THE NORTH ROCK STREAM

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ORDOVICIC-SILURIC SECTION OF THE MINGAN AND ANTICOSTI ISLANDS, GULF OF SAINT LAWRENCE[1]

BY CHARLES SCHUCHERT AND W. H. TWENHOFEL

(Presented before the Paleontological Society December 30, 1909)

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[1] Manuscript received by the Secretary of the Geological Society July 15, 1910.

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Introduction

In 1856 James Richardson, of the Geological Survey of Canada, spent the months of July, August, and September studying the geology of Anticosti and the Mingan Islands to the north, adjacent to the south shore of Labrador, now Quebec. His collection was a large one, consisting of forty boxes and barrels of fossils. The result of this study was the determination of a section beginning early in Ordovicic time, having a thickness of 540 feet, followed by 19 miles of sea, when the section again begins high in the Ordovicic and continues well up into the Siluric through 2,300 feet of limestones and shales.[2]

Richardson's sections are in all essentials still correct and the stratigraphic foundation upon which all subsequent work for this region must be based.

The fossils of Anticosti were studied by Billings, and he states that during his preliminary work "an opportunity was afforded me of examining these in connection with Professor Hall, the eminent Palæontologist of the State of New York, who was then on a visit to this city [Montreal]." This joint examination made it all the more possible for Billings to make the correlations that have since stood unchallenged.[3] His conclusions are as follows:

> "All the facts tend to show that these strata were accumulated in a quiet sea in uninterrupted succession during that period in which the upper part of the Hudson River group, the Oneida conglomerate, the Medina sandstone, and the Clinton group were in the course of being deposited in that part of the Palæozoic ocean now constituting the State of New York, and some of the countries adjacent. If this view be correct, then the Anticosti rocks become highly interesting, because they give us in great perfection, a fauna hitherto unknown to the Palæontology of North America. When the great thickness of

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[2] Richardson: Geological Survey of Canada, Report of Progress, 1857, pp. 191-245.
[3] Billings: Ibidem, 1857, pp. 247-255.

the rocks between the Hudson River and Clinton groups is considered, it becomes evident that a vast period of time must have passed away during their deposition; and yet as the Oneida conglomerate is unfossiliferous and the Medina sandstone has yielded but a few inconspicuous species, we have been almost wholly without the means of ascertaining the natural history of the American seas of that epoch. The fossils of the middle portion of the rocks of Anticosti fill this blank exactly, and furnish us with the materials for connecting the Hudson River group with the Clinton, by beds of passage containing some of the characteristic fossils of both formations, associated with many new species which do not occur in either."

On the basis of Richardson's work and the fossils gathered by him, Billings divided the 2,300 feet of Anticosti strata into six divisions, to which he applied the first six letters of the alphabet. The lower 960 feet are of Divisions A and B, and to him it appeared "very probable that these divisions are a portion of the Hudson River group." They terminate his lower Silurian. To these must be added his Division C, as it has the fauna of the other two divisions.

In 1857 the "Hudson River group" of New York was terminated by the Lorraine, and nothing that is now embraced under the term Richmondian was then known to occur above the Pulaski and Lorraine formations. In reality the "Hudson River group" of the Hudson River Valley is based on the very thick and greatly deformed mass of black shales holding an Atlantic province fauna mainly of graptolites that are older than the Utica and younger than the Cambric. In fact, the term is practically synonymous with the "Quebec group." The "Hudson River group," however, was already extended at that time to include the Ordovicic strata of the Ohio Valley, now known as the Cincinnatian series, or Cincinnatic system, which not only has the equivalents of the Lorraine, but is the typical area for the Richmondian series. The use Billings here makes of the term "Hudson River group" is in the sense of the Lorraine equivalents; but the Anticosti Divisions A and B are not of this time, but of the higher Richmondian series. As yet, no strata of Lorraine time have been shown to occur on Anticosti or in the Saint Lawrence Valley; but even though such may occur in both regions, Billings had in mind the correlation of Divisions A and B of the Anticosti strata with the Lorraine of New York and its equivalents about Cincinnati. Therefore we must modernize Billings's "Hudson River" strata of Anticosti as the equivalents of the Cincinnatian series.

The remaining strata of Anticosti he divided into Divisions C, D, E, and F, that together "constitute a series of deposits to which it is proposed . . . to give the name of the Anticosti group." "The fossils of the middle portion of the rocks of Anticosti [that is, C and D, he thought filled the time of the unfossiliferous Oneida conglomerate and the Medina sandstone] . . . furnish us with the materials for connecting the Hudson River group with the Clinton, by beds of passage containing some of the characteristic fossils of both formations, associated with many species which do not occur in either." We now know that the Oneida is another phase of the upper or marine Medina,[4] and it is still true that these formations have yielded in New York as yet but a very meager fauna. On later pages it will be shown that the Medina at Hamilton, Ontario, yields a small "Clinton" fauna, and that by combining all that is known in regard to this formation it appears probable that this time equivalent is represented by the lower middle part of Division D on Anticosti. In any event, it is true that the Anticosti strata represent a longer and less broken series of marine deposits bridging the time between the latest Ordovicic, or rather the Cincinnatic, and the earliest Siluric than those at any other place in North America.

It will also be seen that the "Anticosti group" of Billings embraces the stratigraphic equivalent of the "Niagara period" as defined by Dana[5]—that is, the Oneida and Medina, the Clinton group, and the Niagara shale and limestone. This usage by Dana was an extension of the term "Niagara group" proposed by the New York State Geologists in 1842, at which time it embraced only what is now known as the Rochester shale and Lockport dolomite. To the Medina, Clinton, and Niagara group the term "Ontario division" was applied by the latter. Clarke and Schuchert[6] used Ontario in the sense of a period or system, and accepted the delimitation of it as given by Emmons (1842), who added to the formations mentioned above the Salina and Waterlime—that is, in modern terms, the Cayugan series of Clarke and Schuchert.

At present we know of no time break in the Divisions D and E of Anticosti; the break, if any, occurs between C and D. Divisions A, B, and the greater part of C have the Cincinnatic faunas, while the life of D and E becomes more and more like that of the Clinton of New York. The strata of Division F, petrologically, are markedly different from those of the other divisions, and the fauna, although not so well known by reason of poor preservation, gives every evidence of being younger than any Clinton biota. Restricting the term "Anticosti group" of Billings to Divisions D, E, and F, therefore, gives to it strata embracing the same geologic time as that covered by the Niagara period of Dana. Billings's term is of 1857. If restricted as above indicated, it will date from the

[4] Hartnagel: New York State Museum, Bulletin 107, 1906, extract 5-7.
[5] Dana: Manual of Geology, first edition, 1863, p. 229; fourth edition, 1895, p. 535.
[6] Clarke and Schuchert: Science, December 15, 1899, p. 875.

publication of this paper. The term Niagara, on the other hand, dates from 1842, and Dana's wider extension was made in 1863. The term Niagara is firmly fixed in American geological literature and has the added value of belonging to the New York standard, the standard section for correlation in eastern North America. These facts, coupled with strict priority of definition of the two terms, have led the writers to the conclusion that Billings's term must yield to Dana's and the modernized term Niagaran will be used in this work. Billings's term "Anticostian," although a synonym for Niagaran, will be retained for local application and value.

In subsequent years Billings described in various places the new species gathered by Richardson, and finally in 1866 (with the exception of a revision of Stricklandinia in Palæozoic Fossils, volume II) brought all the information together in his "Catalogues of the Silurian Fossils of the Island of Anticosti."[7] Here the two lower divisions are referred to the "Lower Silurian" and the remainder to the "Middle Silurian-Anticosti group." Finally, in 1863 Logan[8] gave a very good synopsis of the stratigraphy of the Mingan and Anticosti sections which has become the standard of reference for these strata.

The senior author spent the month of June, 1908, on Anticosti, and studied the entire Anticosti section that may be seen on the southwestern side of the island from English Head to the Jumpers. The junior author devoted the months of July, August, and September of the following year to the same end, circumnavigated the island, studying the strata of the entire shore, and studied as well the western Mingan Islands. By the kindness of the owner of Anticosti Island, M. Henri Menier, we were permitted to do this work. A cod-fishing boat and two men were placed at our disposal and our work was further greatly facilitated through the care and advice we received from the friend and legal adviser of the owner, Mr. Georges Martin-Zédé, and the local governor, Mr. Alfred Malouin.

General Statement of the geologic Sequence

The Paleozoic strata of the Mingan and Anticosti Islands lie nearly horizontal, but there is a definite dip to the south that appears to be somewhat undulatory, "with an average slope of about ninety feet in a mile" (Logan, 1863, page 220). This is the probable average dip for the Mingan Island region, but there is no way of proving that the same

[7] Billings: Geological Survey of Canada, Catalogues of the Silurian Fossils of the Island of Anticosti, 1866, pp. 1-82.

[8] Logan: Geology of Canada, 1863, pp. 119-122, 134-135, 164, 287; 220-224, 298-309.

angle is maintained under the sea for 19 miles, the distance to Anticosti. Richardson and Logan estimated that in this covered interval are hidden about 1,700 feet of strata between the highest deposits of Mingan and the lowest of Anticosti. The latter states that "this volume probably consists of the upper part of the Birdseye and Black River, with the Trenton, the Utica, and the lower part of the Hudson River formation, what is considered the upper part of the latter being the first rock met with on the north side of Anticosti" (Logan, 1863, page 221). The writers will show that strata of probable early Richmondian age are immediately beneath the base of the Anticosti series, and that, as the highest rocks of the Mingan Islands are probably of Black River time, this covered interval may have deposits ranging from the lowest Trenton to the Lorraine. The thickness of 1,700 feet, if present, is not thought to be excessive for these strata, as all formations here have a greater thickness than are known outside of the Saint Lawrence embayment.

The north side of Anticosti Island is far higher—in places 400 feet—and more precipitous than the south shore. There also are seen the oldest strata, the greater part of the north shore being composed of the Richmondian beds. The dip here is also to the south, with the beds of the east and west ends of the island somewhat elevated, so that the deposits of the medial portion of the island now lie nearly horizontal in a shallow trough.

That the strata of Anticosti are the deposits of a very shallow sea—that is, within the zone of wave action, known to extend in the present seas to a depth of about 150 feet—is proven by the many zones of intraformational conglomerates and limestone conglomerates made up of thin flat pebbles in Divisions A, B, and D, by the abundance of reef corals and coral reefs in the higher beds of C and throughout D and E, by the quartz sand and coral sand deposits seen only along the north shore in C and D, and the more or less argillaceous limestones and interbedded zones of shale or thick beds of shale. Some of the intraformational conglomerate beds consist of the churned up sea bottom, in places upending the newly deposited beds for a thickness of not less than 2 feet or rolling the then soft deposits into mud balls. Such are often seen in Divisions A and D.

The general stratigraphic sequence from the Quebec shore to the south side of the Mingan Islands is as follows:

Laurentian.
Canadic system.[9]
Beekmantown series: Feet
Romaine dolomites, with a thickness of at least...... 290

	Feet
Ordovicic system.[9]	
Chazian and Mohawkian series:	
Mingan limestones, etcetera	250
Covered by the sea—Logan's estimate	1,700

The long ranging Species

On Anticosti many of the species have a very long time range, often extending through several hundred feet of limestones. This is to be explained not only by the probable rapid deposition of the Cincinnatic and Siluric formations, but rather in that the Gulf of Saint Lawrence embayment was then on the edge of the continent, on the continental platform in close and open connection with the North Atlantic (Poseidon) Ocean; in other words, near the great reservoir of equable environment and longer enduring faunas. The more striking cases are the following species, with their vertical range given in feet:

Favosites prolificus gradually changes into *F. gothlandicus,* and ranges throughout the entire strata of this island, 2,300 feet. All of the tabulate corals have an extended range, but none are so long enduring as this species.

Beatricea nodulosa and *undulata,* 700 feet.
Hebertella maria, 1,027 feet.
Dinorthis porcata appears twice, first near the base of A and again nearly 800 feet higher in C_1–C_6.
Orthis laurentina, about 100 feet.
Leptæna nitens, 1,060 feet.
Strophomena fluctuosa, 980 feet.
Triplecia ortoni, 280 feet.
Clitambonites diversus, 720 feet.
Parastrophia reversa, 110 feet.
Stricklandinia lens, 540 feet.
Pentamerus oblongus, 650 feet.
Rhynchotrema anticostiensis, 1,060 feet.
Rhynchotrema perlamellosa, 275 feet.
Rhynchonella (?) *janea,* 761 feet.
Catazyga anticostiensis, 320 feet on south shore and 430 feet on north shore.
Anoplotheca hemispherica, 650 feet.
Atrypa marginalis, 230 feet.
Hyattella congesta, over 350 feet.
Hindella umbonata, about 150 feet.
Conradella pannosa, 980 feet.

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[9] Schuchert: Bulletin of the Geological Society of America, vol. 20, 1910, pp. 526-533.

Geologic Section of Anticosti Island

The section begins with the youngest strata along the south shore.
Total thickness, 2,372 feet (Siluric, 1,233, and Cincinnatic, 1,139 feet).

System	Series	Stage	Divisions	in feet	Faunal zones	Correlations	
Siluric	Niagaran (Anticostian)	Chicotte 73	F_{3-4}	55	Crinoidal limestone		
			F_{1-2}	18			
		Jupiter River 561	E_{10}	158	*Stricklandinia lens*	New York Clinton	Clinton faunal aspect
			E_{8-9}	138			
			E_{6-7}	13			
			E_5	43	*Oncoceras futile*		
			E_4	22			
			E_3	80	*Triplecia ortoni*	Ohio Clinton	
			E_2	80			
			E_1	27			
		Gun River 400	D_9	92			
			D_8	65	*Hyattella congesta*	? Upper Medina ? Edgewood	
			D_7	113			
			D_6	60			
			D_5	70			
		Becsie River 199	D_4	60	*Clorinda barrandii*	Probably unknown in United States	
			D_3	35	*Phænopora expansa*		
			D_2	42			
			D_1	62			

Cincinnatic	Gamachian.	Ellis Bay 180	C_{11}	10	First marked coral reefs	Unknown in United States
			C_{10}	10		
			C_9	12	*Hormotoma gigantea* Last Beatricea	
			C_8	21	*Parastrophia reversa*	
			C_7	41		
			C_6	20		
			C_5	6	*Dinorthis porcata*	
			C_{1-4}	60	First abundance	
	Richmondian	Charleton 730	B_{11}	96	Beatricea	Richmondian of Mississippian Sea
			B_{10}	165		
			B_{7-9}	179		
			B_6	102		
			B_{3-5}	133	*Rhynchotrema perlamellosa*	
			B_{1-2}	55		
		English Head 229	A_6	1	"Track bed"	
			A_5	86	Dinobolus	
			A_4	63		
			A_3	10	Early Richmondian	
			A_2	25		
			A_1	44		Sea-level
		Macastey black shale			? Earliest Richmondian	

Mingan Islands Succession

CANADIC SYSTEM. BEEKMANTOWN SERIES

Romaine formation—thickness and general characteristics.—In the region of the Mingan Islands the Beekmantown deposits are seen at various places between Saint John River eastward to Sainte Geneviève Island, a distance of about 55 miles. The thickness of the Beekmantown, which will hereafter in this paper be called the *Romaine formation* (from the island of the same name at the mouth of Romaine River), is probably not less than 290 feet and not more than 365 feet. Logan estimated it at not over 250 feet, but he excluded about 90 feet that are herein included. These deposits consist of dolomites and magnesian limestones with thin bands of shale or shaly magnesian limestone.

Romaine formation, Division A_1.—In the basal portion the dolomites are more granular than in the higher strata and locally are greatly disturbed by the diagenetic changes that have taken place during or shortly after the time of deposition. The rock in such places appears as if kneaded, and has many geodes, nodules, and patches of yellowish white chert and yellowish white calcspar. These phenomena have been described by Logan, who states that they "suggest the idea that they may be the effect of ancient springs, which rise to the surface through the yet unconsolidated sediment, washing away the finer particles, and disturbing and confusing the arrangement of the strata" (Logan, 1863, page 121). Similar phenomena have been seen elsewhere in Beekmantown deposits and are thought to be produced by the dolomitization of the yet unconsolidated limestones.

The Romaine A_1 beds undoubtedly rest directly on the Laurentian, although an actual contact has not been seen. The oldest observed strata are on Romaine Island, and about one-eighth of a mile northward occurs the Laurentian granite, the interval being concealed by a shallow channel that is rapidly being filled in by sands. The strata concealed here are estimated not to exceed 30 feet. It is probable that in this concealed zone occur the strata described by Logan as follows:

> "At the east horn of Pillage Bay, on the main coast, opposite to Hunter's Island of the Mingan group, a white sandstone about eight feet thick has been met with resting on Laurentian gneiss. The position of this sandstone, and the moderate dip of the palæozoic strata in that neighborhood, would bring it to within two feet of the nearest strata of the Calciferous formation" (1863, page 287).

The Romaine Island section exposes at the base a shaly limestone not over 3 feet in thickness, followed by a mottled dark gray, coarsely crystalline dolomite of 40 feet thickness. This is the kneaded or locally altered zone mentioned above. Fossils are very scarce here, the only one seen being *Trochonema tricarinatum* Billings. From this island was obtained by Richardson *Archæoscyphia minganese* (Billings).

The Romaine Island section may again be seen, and to better advantage, on Mingan Island opposite the Hudson Bay Company post of this region. Here the lower 35 feet appear to be the direct continuation of the 40 feet of mottled dark gray dolomites of Romaine Island, and have yielded *Raphistomina laurentina* (Billings).

The higher beds of Mingan Island, or Romaine A_2, having a thickness of 23 feet, are more finely crystalline and better stratified dolomites in beds from 12 to 32 inches thick, and have yielded *Fusispira calcifera* (Billings) and *Piloceras canadense* Billings. These identical beds are in all probability also exposed on Hunter and Sainte Geneviève Islands, where Billings reports the occurrence of *Piloceras canadense.*

On the Quebec coast, in the bay west of Clear Water Point, are seen mottled and gray dolomites having a thickness between 80 and 100 feet. While no fossils were seen in these deposits, their character and position locate them as in part equivalent to the strata of Romaine and Mingan Islands.

Romaine formation, Division B.—The higher strata above the Mingan Island section are beneath the southern part of the channel between Romaine and Large Islands. The thickness of the beds in this interval is estimated at between 150 and 200 feet, the lesser depth being the more probable one.

Romaine formation, Division C.—The Romaine strata are again visible on Large Island, where the section is continued, the basal 75 feet consisting of yellowish gray and dull drab colored, fine grained magnesian limestone carrying chert nodules, with a few beds of dark shale. The limestone beds range up to 2 feet in thickness. Logan has erroneously referred these Large Island beds, with a thickness of 65 feet 5 inches, to the Chazy series (Logan, 1863, page 134). The only organic remains seen here are fucoid markings and *Bathyurus amplimarginatus* Billings ?. These beds are followed by others, of which all but the basal portions are concealed, and may be seen on the reefs near the middle of the west side of the island. Here the lower 15 feet have yielded *Billingsella* (?) *grandæva* (Billings), *Syntrophia lateralis* (Whitfield) ?, *Bathyurus amplimarginatus,* and *Leperditia* n. sp.

The *Syntrophia* beds are again met with on Parroquet Island, where the basal 15 feet have yielded *Syntrophia lateralis* ?, *Euomphalus* cf. *perkinsi* Whitfield, and an undetermined *Bathyurus.* This same horizon is thought to be present in the lowest 16 feet of the section of Quarry Island, the island directly east of Large Island, in the lowest 17 feet of Harbor Island opposite Esquimaux Point, and at Clear Water Point.

Correlations.—In the Mingan region the oldest Paleozoic strata are of Beekmantown time. To the northeast it is nearly 300 miles to the lower Cambric of the Straits of Belle Isle, and to the southwest of the Mingans lower and upper Cambric fossils occur in the conglomerates of the Quebec series. It is therefore evident that while there are no strata of Cambric time now in the immediate vicinity of the Mingans, that sea may have extended across these islands, in which event its deposits were removed during the long land interval preceding late Beekmantown time.

From the fossils cited above, it is certain that the Beekmantown strata of the Mingan Islands are not older than the Fort Cassin beds of the Lake Champlain area, and, further, it is probable that they are not older than zone D_4 of Brainerd and Seely's section.[10] This is the richly fossiliferous horizon of the Fort Cassin formation (upper Beekmantown) and the only one here having *Piloceras*. Its thickness is 100 feet, above which are 470 feet of limestones constituting zone F. It is probable that the Mingan Beekmantown represents all of D_4 and some or all of E of the Lake Champlain sequence. Between E and the Chazian series of this area there is a stratigraphic break, and the same emergence is present in the section of the Mingan Islands.

ORDOVICIC SYSTEM. CHAZIAN AND MOHAWKIAN SERIES

Mingan formation—thickness and general characteristics.—Above the Beekmantown or Romaine strata follows disconformably, the disconformity being indicated by a basal conglomerate, a series of limestones that will be referred to as the *Mingan formation* (after the Mingan Islands), having a visible thickness of about 250 feet. This estimate is based on the depth of the strata of Large Island above the conglomerate zone, plus the Bald Island section. It is probable, however, that the lowest beds of Bald Island are the equivalent of a portion of the upper strata of Large Island. On this basis the Mingan series has a thickness of not more than 240 feet. The limestones of the Mingan series in all probability continue to a greater thickness in the north channel of the Saint Lawrence toward the island of Anticosti. Richardson thought that 1,700 feet of strata are here concealed. Logan, in his account of these strata (Logan, 1863, pages 134–135), gives the thickness of the "Chazy" and "Black River" formations as 357 feet, but as the equivalent of the New

[10] Brainerd and Seely: Bulletin of the American Museum of Natural History, vol. iii, 1890, pp. 1-23.

York Black River is not seen here, and as the lower 65 feet of his Large Island section are now known to belong to the Romaine series, his thickness for the Mingan series reduces to 292 feet, which is still 50 feet greater than the writers' measurements.

Mingan formation, Zone A_1.—The basal strata of the Mingan series have been seen in contact with the Romaine formation on Quarry Island, on the east side of Deep Cove of Large Island, on Harbor Island, and on Parroquet Island. In these places it is a gray to white coarse sandstone or conglomerate of quartz pebbles, and in all observed cases is decidedly cross-bedded. This zone varies in thickness from 18 inches (Quarry Island) to 5 feet (Deep Cove). Therefore there are here the invading shore deposits of the Chazian sea over the then land of Beekmantown dolomites. The fossils here are rolled and broken individuals of *Orthis ignicula* and *Rhynchotrema* (?) *orientalis.* The basal conglomerate is absent on Parroquet Island and was not observed at Clear Water Point, as the Romaine series is here directly followed by the shales of the next division.

Mingan formation, Zone A_2.—The conglomerate zone is followed by a variable series of shales, calcareous sandstones, and limestones having a united thickness varying between 10 and 20 feet. These beds may be known as Mingan A_2 zone. On Quarry Island, where the conglomerate is 5 feet thick, there follows dark greenish arenaceous shale with a thickness of 7 feet, while that on Large Island is 11 feet thick. On Quarry Island this shale is succeeded by a yellow to light green, fine grained, highly calcareous sandstone between 4 and 5 feet thick, a bed of greenish arenaceous limestone, and finally 20 inches of green arenaceous shale with thin sandstones that locally may change into a brittle greenish limestone.

On the Parroquet Islands, where the basal conglomerate does not occur, the Romaine series is followed directly by a zone of dark greenish to black, rusty weathering shale that is nearly 6 feet thick. Above this is a 6-inch zone of white granular limestone (wanting on the north side of the island), followed by more dark greenish carbonaceous shale slightly micaceous, having a thickness of between 6 and 8 feet. In these higher shales there are fragments of *Lingula, Conularia,* and *Serpulites dissolutus* ?. Then follows a greenish white limestone 2 feet thick and a final green shale zone of 10 inches.

On Phantom Island, east of Quarry Island, above the conglomerate there follows a dark greenish to black shale 6 feet thick, but thinning to less than 3 feet when traced eastward; then 4 feet of calcareous sandstone, 20 inches of dark shales, and 5 feet of arenaceous limestone that is locally shaly. At Clear Water Point the base of the Mingan series is not well exposed, but the basal conglomerate appears to be absent immediately above a zone 20 feet thick of yellowish gray limestone that is here regarded as the top of the Romaine series. Logan (Logan, 1863, page 134) gives the thickness of these same beds as 28 feet, and it is probable that he included in his estimate the higher 8 to 10 feet of strata which the writers of the present paper will place at the bottom of the Mingan. This series will then begin here with a gray, yellowish and bluish fine grained, highly calcareous, thin-bedded sandstone 42 inches in thickness, followed by 6 inches of green shale, 2 feet of calcareous sandstone, and finally by 4 feet of green more or less nodular shale.

On Harbor Island the conglomerate, which is here 3 feet 8 inches thick, is followed by 4 feet of green arenaceous shale, 8 feet of shale and shaly limestone, and about 3 feet of calcareous sandstone.

The Mingan zones A_1 and A_2 are, therefore, seen to be very variable in character in closely adjacent areas, and this is especially true for the higher zone. There is here the unmistakable physical evidence of a very variable shore character, just such as would be expected at the margin of an invading sea.

Mingan formation, Zone A_3.—The shale beds are followed by gray to light greenish, more or less thin-bedded limestones that locally have more or less thin zones of shale in the lower part. On Quarry Island this zone is about 45 feet thick, the lower 10 feet of which are rich in fossils. On the Parroquet group, about 30 feet of this zone are exposed when the section passes beneath the sea. On Phantom Island the uppermost 15 to 20 feet are of this zone and represent the lower fossiliferous portion of Quarry Island. The upper 50 feet of Harbor Island, with the possible exception of the higher beds, are also of this horizon with the greatest abundance of fossils in the lower portion. At Clear Water Point this zone begins with the nodular fossiliferous limestone 10 feet thick, followed by 25 feet of gray and brownish gray dense limestone.

The fauna of the lower 10 to 15 feet of Mingan A_3 zone may have upwards of 60 species, among which the following are either the most abundant in individuals, or are of described species, or forms thought to be guide fossils to the horizon[11] (the species marked with a * occur in the Chazy of New York): *Eospongia rœmeri, *Zittelella varians, *Strephochetus* cf. *ocellatus*, *Solenopora compacta* var., *Inocaulis* n. sp., **Stylarœa parva*, *Bolboporites* (very rare), **Schizambon duplicimuratus*, *Bythotrypa*, *Crepipora*, *Stictoporella* cf. *angularis*, *Rhinidictya mutabilis*

[11] For many of these identifications the authors are indebted to Dr. E. O. Ulrich and Dr. Percy E. Raymond.

major, Phylloporina cf. *sublaxa, Nicholsonella, Batostoma varium, Eridotrypa mutabilis,* **Orthis ignicula,* **Hebertella exfoliata* ?, *Clitambonites piger,* **Leptæna incrassata* (rare), **Rafinesquina champlainensis, Strophomena* (group of *S. sulcata*), *Rhynchotrema* (?) *orientalis,* **Camarella varians,* **C. longirostra, Zygospira* (small finely plicate form), *Maclurites atlanticus* (cf. *M. bigsbyi,* a Lowville guide fossil), **Eccyliomphalus* cf. *fredericki,* **Raphistoma striatum,* **R. stamineum* ?, *Tetranota* near *bidorsata, Oncoceras* cf. *lyceum, Poterioceras, Cameroceras,* **Spyroceras* cf. *clintoni,* **Plectoceras jason, Leperditia* two species, **Bumastus globosus,* **Thaleops clavifrons,* **Isotelus harrisi, Illænus bayfieldi,* **Pliomerops canadensis,* **Pterygometopus annulatus, Bathyurellus fraternus, Bathyurus angelini,* and **Eoharpes* cf. *antiquatus.*

The following additional species described by Billings are thought to be from this zone, and not from the "Calciferous," as he states: *Conocardium blumenbachi, Pleurotomaria abrupta, P. misera, Helicotoma perstriata, Cœlocaulis linearis, Solenospira prisca, Lophospira aspera, Cyrtoceras maccoyi, Plectoceras tyrans,* and *P. natator.*

The higher beds of Mingan A_3 have as yet yielded no fossils.

Mingan formation, Zone A_4.—On Large Island, to the south of the concealed zone that is established by Richardson at about 56 feet, are seen 5 feet of the brittle limestone thought to be the top of the 45 feet of limestone composing zone Mingan A_3. This is followed by 45 feet of light drab, dense, "birdseye"-like limestone that weathers into the fantastic forms referred to by Richardson[12] as the "flower pot rocks." No determinable fossils were seen here, but on one of the smaller of the southeastern islands in the Parroquet group a few fossils were obtained in the lower half of this zone. These are *Orthis ignicula, Camarella varians, Bathyurus extans,* and *Bumastus* cf. *globosus.*

It is probable that some of the highest strata of Harbor Island also belong here and, as well, 35 feet of the lowest beds of Bald Island, as at this place "flower pots" occur, but at neither of the two places have these deposits yielded fossils.

Mingan formation, Zone A_5.—The previous zone of Large Island is followed farther south on the same island by from 35 to 40 feet of light colored, dense, brittle limestone, also having more or less of a "birdseye" character. It forms Tower Rock and the south end of Large Island. Few fossils were collected, among them being *Leperditia, Thaleops clavifrons, Bumastus globosus,* and *Bumastus erastusi.*

Billings records here the presence (probably from the topmost beds) of *Maclurites logani, Euconia amphitrite, Cyrtoceras subturbinatum,*

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[12] Richardson: Report of Progress, Geological Survey of Canada, 1857, p. 242.

Orthoceras minganense, O. cornuum, Thaleops clavifrons, Thaleops arctura, and *Bumastus trentonensis.*

This same series of limestones is seen to better advantage and with a greater thickness on Bald Island, due to an upward flexure of the strata. The zone A_5 begins here 35 feet above the basal limestones, and is about 65 feet thick. It consists of coarsely granular, white limestones almost chalky in spots, not well bedded below, but better stratified above. The lower half is a fossil breccia with much crystalline calcite and diagenetic destruction of the fossils. It has furnished, among others, the following forms: *Solenopora compacta, Ischadites, *Stylaræa parva, Phylloporina sublaxa* (Lowville type), *Rhinidictya mutabilis,* and variety *major, Eridotrypa mutabilis, *Orthis ignicula, Hebertella* cf. *bellarugosa, *H. exfoliata* ?, **Camarella varians, *Rhynchotrema* (?) *prinstana, *Rafinesquina champlainensis, *Leptæna incrassata* (common), *Maclurites logani, Strophostylus* cf. *textilis, Holopea* cf. *pyrene, *Conocardium beecheri, Oncoceras* two species, *Poterioceras, Cyrtocerina* cf. *typica, Spyroceras, Cameroceras, Leperditia, Leperditella, Bythocypris, *Bumastus erastusi, *B. globosus, *Amphilichas minganensis, *Ceraurus pompilius, Bathyurellus brevispinus, Glaphurus,* and **Pseudosphærexochus vulcanus* ?.

Zone A_5 is closed by a fine grained, dense, whitish limestone 28 feet thick, with bands of granular limestone. These beds are not well exposed on Bald Island, but on a smaller island immediately to the southwest they can be seen to advantage. The only fossils gathered are large *Leperditia.*

Correlations.—The few species known from the introductory Mingan zones A_1 and A_2 link them directly with zone A_3. Their strata represent the near shore sediments of the invading sea and in the basal quartz conglomerate the brachiopods consist of separated valves that also show wear due to wave action. The fauna of A_3 is abundant, and begins with a profusion of *Rhynchotrema* (?) *orientalis.* When this biota is all determined it may attain to 60 species, and at first sight gives one the impression that it is of middle Chazian time. This is due to the presence of many Chazian species (see the list on pages 690-1), and particularly of *Stylaræa parva, Bolboporites, Leptæna incrassata, Camarella varians, C. longirostra, Maclurites atlanticus, Bumastus globosus,* and *Pliomerops canadensis.* On the other hand, an abundance of bryozoa (rare in the lower and middle Chazy), the sponge *Zittelella varians,* and the brachiopods *Orthis ignicula* and *Hebertella exfoliata* ? give the fauna an early Black River aspect. It was this Mohawkian impress that led the writers to believe these lower zones of the Mingan series to be not older than upper Chazy, and their first inclination was to refer them to even younger beds—that is, to the Lowville and equivalent deposits. Some of the species were then sent to Raymond, and from what he has seen he is inclined to correlate the Mingan A_3 and A_5 zones with the middle Chazy and the "reef fauna at the base of the upper Chazy at Valcour Island, Chazy, and Isle La Motte. *Bumastus erastusi* and *Conocardium beecheri* are not abundant there, and all the other species sent me are common at that horizon." Billings, on the other hand, thought this higher zone of the Mingan series to be of Black River age.

A larger series was later sent to Ulrich, and as he has collected very similar faunas in widely distributed localities throughout the eastern United States, it was thought that he would find it easy to make definite time correlations. On the contrary, he found the determination of the ages of the beds in the Mingan series to be a matter of great difficulty. This because "the faunal evidence is on the whole so mixed in its suggestions that I question if the problem can be determined satisfactorily at present." Ulrich sees no lower Chazy at all in the Mingan series, and he is not even certain that there is any middle Chazy here. He writes: "According to the faunal evidence, the beds containing the A_3 biota can not be older than upper Chazy, and it may be a recurrent and modified phase of the north Atlantic fauna in Black River time." As for the white limestone fauna of zone A_5, "it is of Black River age, and probably represents a late rather than an early stage of that group. It is clearly a later phase of the A_3 fauna with the addition of the mollusca, which commonly go with such a rock."

For the present the Mingan zones A_1 to A_3 are tentatively correlated with the upper Chazy of New York, and A_5 with the earlier stages of the Black River. Accordingly, zone A_4 holds the horizon of the Lowville of New York.

Anticosti Island Succession

ORDOVICIC SYSTEM. MACASTEY BLACK SHALE

Location and characteristics.—Along the northwest end of Anticosti from English Head east to Macastey Bay the sea throws up a black shale. At the latter place the junior author in 1909 found considerable quantities of this shale along the beach, and in a few places large blocks, particularly at Macastey Mountain, indicating that these deposits are in the immediate shallow water outside the reef fringing the island here. This occurrence has added value, in that it indicates that the Anticosti strata of Richmondian time repose directly on these black shales. In regard to the nature of the contact nothing is known, nor is anything known concerning the lower formation upon which it rests. For these reasons it is proposed to call it the Macastey black shale, so as not to confound it with the Utica black shale with which it has been correlated.

The shale has the physical character of the typical Utica—that is, a black, highly carbonaceous material here rich in fossils, but of few species, some of which are replaced by iron sulphide. The common fossils are *Climacograptus bicornis, C.* n. sp. near *typicalis, Leptobolus insignis, Endoceras proteiforme,* and *Triarthrus spinosus.*

Correlation.—At first sight this little biota and the character of the black shale gives one the impression that it is of the time of the Utica formation of New York. While some of the species obtained are also found in the typical Utica, others have not been found in New York. The absence of *Triarthrus becki,* the common trilobite of this horizon, is suspicious, and raises the question whether the Macastey black shale may not be of later time. At Ottawa, Canada, the "Utica" has *Asaphus canadensis* associated with *Triarthrus spinosus,* and these underlie shales of the "Hudson River," which have, among other fossils, *Catazyga headi.* On Anticosti a local variety of the latter, *C. anticostiensis,* is associated with an undoubted Richmondian fauna, and as the genus *Catazyga* is unknown in older strata, the writers are led to believe that the Macastey black shale may also be of Richmondian time. The "Hudson River" shales are very widely distributed in the Saint Lawrence Valley, and at several widely separated places have yielded either *Catazyga* or *Beatricea* (Ottawa, Three Rivers, Lake Saint John), genera that unmistakably point to Richmondian time. The writers are therefore led to believe that the Macastey black shale is rather of early Richmondian than of late Mohawkian or Utica time.

CINCINNATIC SYSTEM. RICHMONDIAN SERIES

General discussion of the series.—The visible strata of Anticosti, not less than 2,372 feet in thickness, are apparently of one uninterrupted sequence, beginning early in Richmondian time and persisting into what appears to be the equivalent of the Rochester stage of the Siluric. It will be shown that the faunas of the lower 1,139 feet are those known elsewhere in part as the Richmondian, while the upper 1,233 feet have the early Siluric aspect, and form a series of deposits to which Billings applied the term "Anticosti group," here changed to Anticostian series (= Niagaran) in conformity with modern usage.

According to Richardson, the combined thickness of the strata of Anticosti is 2,321 feet, and the authors' restudy of his careful work determines a very similar thickness. These strata are essentially thin-bedded interstratified limestone and shales with a few thick zones of pure limestone and shale and rarely horizons of sandstone. The zonal classification here adopted is in the main that of Richardson, first published in 1857 and later slightly changed by Logan.[13] The "Hudson River group" of Billings[14] and the basal division of his "Anticosti group" are here referred to the Richmondian, and for the main part of his second group the series term Niagara will be used.

The Richmondian series of Anticosti is clearly divisible into the three divisions as defined by Richardson. His Division A is best seen at the western end of the island at English Head, and these strata will here be referred to the *English Head formation.* Division B is well exposed on the north side at Charleton Point and Observation Cliff. The latter place is difficult of access, but at the former locality may be collected an abundance of fossils, and for this reason these strata will be named the *Charleton formation.* Richardson's Division C must on faunal grounds be divided, and this designation will be retained only for the lower 180 feet, the remainder of his C zones, C_{12}–C_{14}, which have a thickness of 139 feet, being referred to his Division D. These lower beds of C are best studied about Ellis Bay, and they will be here named the *Ellis Bay formation,* the higher beds being referred to the *Becsie River formation.*

English Head formation (*Richardson's Division A*).—The thickness of this formation is about 229 feet, and is divided by Richardson into six zones, here numbered A_1 to A_6.

The lowest zone of this division, or A_1, is thought to rest on the black Macastey shale. The actual contact can not be seen, but around Macastey Bay large pieces of the black shale are thrown on the shore, presumably by the storms, torn undoubtedly from the shallow depths beyond the reefs. How much of A_1 is concealed by the sea is not determinable. The lowest strata of this zone are found on the reef at English Head, but at that point flakes of the black shale are rarely seen. The shale occurs in greatest abundance in the bay east of Macastey Mountain, where its presence is doubtless explained by increased wave action on perhaps an elevated portion of the sea bottom. In view of these facts, the writers prefer not to make estimates of the thickness that may exist down to the black shale contact. Division A consists of gray to light greenish thin-bedded limestone with thin partings of green and gray shales. At many levels zones of intraformational conglomerates occur locally, attaining to

[13] Richardson: Report of Progress, Geological Survey of Canada, 1857, pp. 206-235. Logan: Geology of Canada, 1863, pp. 221-223, 298-304.

[14] Billings: Catalogues of the Silurian Fossils of the Island of Anticosti, Geological Survey of Canada, 1866, pp. 1-93.

more than 2 feet in thickness, which prove the shallowness of the sea during their deposition.

The strata of this division are seen to best advantage at the west end, on the north side of Anticosti, about English Head and Macastey Bay. To the east of the last named place the lower portion of the capes is formed by the higher beds of A_5 and the "track bed" or A_6, the latter dipping below sea-level at the base of Observation Cliff. Beyond this point no strata of A occur, all the exposures belonging to higher divisions. On the south side of the island Division A is not above sea-level.

The zones of the English Head formation are as follows:

	Feet
Early Richmondian beds.	
A_1. Seen on the reefs about English Head. Thickness	44
A_2. The lower part of English Head	25
A_3. The more fossiliferous lower portion of English Head	10
Dinobolus beds.	
A_4. The main or upper beds making English Head. In the lower portion are zones of *Dinobolus* in the greatest profusion.	63
A_5. Seen to best advantage between English Head and about Macastey Mountain, where portions of the higher beds of A_4 may also be seen	86
A_6. The "track bed," with the impressions known as *Sœrichnites abruptus*, and seen at numerous places from English Bay to Observation Cliff, 6 inches.	

The fauna is a large one and practically the same throughout this division. The more diagnostic forms listed below are in the main derived from A_4 and A_5: *Streptelasma rusticum, Favosites* (?) *prolificus* (attains to 2 feet and more in diameter), *Calapœcia anticostiensis, Climacograptus putillus, Dinobolus,* n. sp. (A_4), *Hebertella maria, Dinorthis porcata, Dalmanella meeki, Strophomena fluctuosa, S. hecuba, Leptæna nitens* (close to *L. unicostata*), *Rhynchotrema anticostiensis, R. perlamellosa* (but a single specimen from lower A_5), *Catazyga anticostiensis, Pterinea prolifica, Conradella pannosa, Liospira americana, Pterotheca* cf. *transversa, Ascoceras* ? large n. sp., *Actinoceras anticostiense, Cameroceras, Ceraurus pleurexanthemus.*

Correlation.—A hasty examination of the fossils of this division may give the impression that their age is that of the Black River or lower Mohawkian, but after further study it is seen that many species are present which elsewhere are known only in the Richmondian. These diagnostic fossils are found more especially to the west of the Cincinnati axis, as at Wilmington, Illinois, and Spring Valley, Minnesota. Such are *Streptelasma rusticum, Climacograptus putillus, Dalmanella meeki,* *Strophomena fluctuosa, Leptæna nitens* or *unicostata, Rhynchotrema anticostiensis,* and *R. perlamellosa.* On the east side of the axis in southwestern Ohio occur *Streptelasma rusticum, Dalmanella meeki, Rhynchotrema perlamellosa,* and *Catazyga headi,* which is a local variation of *C. anticostiensis.*

On the other hand, the strata of Division A continue without break into those of Division B, where the Richmondian fauna is in full development, and it must therefore be concluded that the former division also belongs to the Richmondian epoch. The writers would, therefore, correlate the strata of Division A with the lowest two zones of the Ohio Richmondian—that is, the Arnheim and lower Waynesville. In the Arnheim *R. perlamellosa* does not occur, but is present in the Waynesville—occurrences in harmony with the appearance of this shell on Anticosti. Of course, it is possible that the Anticosti series may have begun somewhat earlier than the appearance of this guide fossil in Ohio, and that therefore the basal zones of A are of highest Maysvillian time. As to this, however, there is at present in the faunas no clear guidance.

If the writers' correlations be correct that the black shale of Macastey Bay is probably of Richmondian time and not the equivalent of the Utica, it follows that there is no time break between this black shale and the limestones of Division A.

Charleton formation (*Richardson's Division B*).—The strata of this division are 730 feet thick and are seen from English Bay east to Junction Cliff on the south side of the island, and on the north side as far east as Table Mountain. Limestone conglomerate beds with small flat pebbles occur throughout and intraformational conglomerates more rarely. The zones of Richardson are grouped as follows:

	Feet
Rhynchotrema perlamellosa beds.	
B_1 and B_2. Gray limestones directly above the "track bed"	55
B_3, B_4, and B_5. Reddish gray limestones with few fossils	133
On the north shore these zones appear to be at least twice as thick, extending through fully 400 feet of strata above the "track bed."	
Beatricea beds.	
B_6. Reddish gray limestone with fossils more abundant	102
Beatricea appear at the base of this zone, and on the south side of the island continue through 702 feet of the higher strata.	
B_7, B_8, and B_9. Gray limestones. Fossils are scarce, but the corals and *Beatricea* are here more common than below	179
B_{10}. Gray limestones	165
B_{11}. Concealed measures on south shore. On north shore the 70 feet of shale at the base of Point Joseph are thought to belong to this zone	96

Zones B_1 and B_2. On the south shore but few fossils are seen in these zones, and the same is true for zones B_3–B_5, all of which species are also those of Division A. On the north shore zones B_1 and B_2 are of less pure limestone with more shale and therefore yield more fossils. These may be seen from White Cliff eastward to the trap dikes of West Cliff. The more diagnostic fossils of these zones (especially of the north shore) are the following: *Favosites* (?) *prolificus, Climacograptus putillus, Reteocrinus fimbriatus, Sceptropora facula, Dinobolus* n. sp. (B_2), *Dinorthis subquadrata, Strophomena neglecta, S. hecuba, Rhynchotrema anticostiensis, R. perlamellosa* (common here), *Catazyga anticostiensis, Byssonychia subrecta, Billingsites canadensis, Isotelus alacer* (of *susæ* group), *Cheirurus icarus,* and *Ceraurus pleurexanthemus.*

Zones B_3, B_4, and B_5. On the south shore these zones are thin-bedded limestones with almost no shale and furnish but very few fossils, while on the north shore they are made up of an alternation of shales and limestones abounding in fossils. At Observation Cliff these strata may be studied to best advantage where there are 15 bands of limestone each about 10 feet thick, alternating with thin limestone and shale zones each about 20 feet in depth. The cliff here is about 350 feet high, at the bottom of which is the "track bed" making the top of Division A. No *Beatricea* were seen here, yet on the south shore they appear for the first time in B_6, or 188 feet above the "track bed." Zones B_3–B_5 have therefore on the north shore fully twice as great a thickness as the equivalent beds near the West End lighthouse of the south shore. At Cape Henry the highest beds of zones B_3–B_5 may be seen, here consisting of 200 feet of thin-bedded limestones of a drab or grayish brown color.

The fauna of these zones is a large one, of which may be mentioned *Streptelasma angulatum, Calapœcia cribriformis, Columnaria halli, Palasterina rugosa, Dendrocrinus latibrachiatus, Reteocrinus fimbriatus,* first abundance of *Nematopora, Arthroclema,* and *Helopora, Cornulites richmondensis, Lingula quadrata, Dinobolus* n. sp. (rare), *Dalmanella meeki, Dinorthis subquadrata, Hebertella maria, Rafinesquina imbrex, R. squamata* or *ceres, Strophomena neglecta, S. fluctuosa, S. hecuba, Leptæna nitens, Rhynchotrema perlamellosa, R. anticostiensis, Rhynchonella* (?) *janea, Catazyga anticostiensis* (ranges throughout these zones on north and south shores), *Conradella pannosa, Billingsites canadensis, Cheirurus icarus, Calymene callicephala, Illænus alacer,* etcetera.

Zone B_6. On the southwest end of Anticosti this zone is seen in the abandoned sea cliff to the west of West End lighthouse. Here it is 102 feet thick. On the northeast end of the island the equivalent strata are well exposed at Battery Point. At both of these places the *Beatricea* make their appearance, but on the north shore not until the upper part of this zone. Other fossils are *Calapœcia anticostiensis, Columnaria alveolata, C. halli, Favosites* (?) *prolificus, Beatricea undulata* (most abundant), *B. nodulosa* (rare), *Dinobolus*, n. sp., *Clitambonites diversus, Leptœna nitens, Rhynchotrema anticostiensis, Rhynchonella* (?) *janea*, etcetera.

Zones B_7–B_{11}. On the southwest shore of the island these beds do not yield a fauna, but *Beatricea* are seen sparingly throughout.

On the north shore the same zones are first seen at Steamer Bow, where 40 feet of thin limestones and shale are exposed, the base being concealed. Following an unexposed area in Broom Bay, there are at Point Joseph 70 feet of arenaceous shale with thin limestone, succeeded by a cross-bedded sandstone. It is at the base of this sandstone (see page 703) that for the present the writers would draw the dividing line between B and C. There is here, then, 110 feet of measured beds and two intervals, each more than a mile long, in which the thickness of the strata is not known. It therefore follows that the thickness of 261 feet for these zones on the south shore is paralleled by a similar depth on the north shore.

Correlation.—In this division there are present many of the typical middle and upper Richmondian fossils of southwestern Ohio (those of the Waynesville to Elkhorn zones)[15] and, as well, others found to the northwest of the Cincinnati axis. It is also to be noted that the very diagnostic *Beatricea* appear in the Saint Lawrence sea above the lower third of Division B, and in the Mississippian sea not earlier than the upper Richmondian at the base of the Liberty beds. In these conditions is thought to exist safe guidance for correlating Anticosti Divisions A and B as about equivalent to all of the Richmondian of the Mississippian sea.

The fossils of zone B of Anticosti that also occur or have close allies in the Richmondian of the Mississippian sea are the following: *Beatricea undulata, B. nodulosa, Calapœcia cribriformis, Columnaria halli, C. alveolata, Favosites* (?) *prolificus, Climacograptus putillus, Reteocrinus fimbriatus, Dendrocrinus latibrachiatus, Palasterina rugosa*, abundance of *Nematopora, Arthroclema, Helopora*, and *Sceptropora facula, Dinorthis subquadrata, Dalmanella meeki, Strophomena neglecta, S. fluctuosa, Leptœna nitens* or *unicostata, Rhynchotrema anticostiensis, R. perlamellosa, Catazyga anticostiensis, Byssonychia subrecta, Conradella pannosa, Cheirurus icarus*, and *Illœnus alacer* (*susœ* group).

The most striking difference between the fauna of Anticosti Divisions

[15] Cumings: Thirty-second Annual Report of the Department of Geology, Indiana, 1907.

A and B when contrasted with the Ohio Richmondian is the almost total absence in the former region of the Trepostomata bryozoa. The Atlantic waters of this time seem to have had no great development of these animals, for the same condition also occurs in Europe. In the Ohio region of the Mississippian sea these bryozoans are in wonderful abundance. To the west of the Cincinnati axis they are also scarce, but here they are more often seen than on Anticosti.

In the Ohio region *Beatricea* ranges from the base of the Liberty to the top of the Elkhorn, a thickness of probably less than 100 feet, but on Anticosti these fossils range through 702 feet of limestones. Here the forms of life generally endured a long time, and the Gulf of Saint Lawrence may be regarded as on the continental shelf in close proximity to the permanent Atlantic (Poseidon) Ocean, where the physical conditions were more equable than in the Mississippian continental sea. Another striking case is the brachiopod *Catazyga headi*, that in the Ohio region is restricted to a very limited zone, usually one of a few inches, while on Anticosti *C. anticostiensis* ranges through all of A and the lower third of B, or through 320 feet (south shore) to 430 feet (north shore) of limestones and shales. *Dinorthis porcata* occurs for the first time in the English Head stage A_4–A_5, and reappears again at the base of the Ellis Bay formation.

At Stony Mountain, Manitoba, occurs a Richmondian fauna that is more clearly related to zone B_6 than to the higher beds. Whiteaves[16] has listed 55 species from this western locality, and of these the following also occur on Anticosti: *Streptelasma rusticum, Favosites* (?) *prolificus, Protaræa vetusta, Beatricea undulata, B. nodulosa, Sceptropora facula, Strophomena neglecta, S. fluctuosa, Rafinesquina ceres, Leptæna nitens, Dinorthis porcata* (the writers have seen this species from Stony Mountain), *Rhynchotrema perlamellosa, R. anticostiensis*, and *Cheirurus icarus*. When the Anticosti fauna is completely known there will certainly be other common species added to the above list.

The Charleton formation is not seen again to the west of Anticosti for 375 miles, when it reappears at Lake Saint John, at the head of the Saguenay. Here Billings reports *Catazyga headi* and *Beatricea*. The next occurrence is at Three Rivers, to the west of Quebec City, more than 500 miles west of Anticosti. *C. headi* also occurs at that locality.

CINCINNATIC SYSTEM. GAMACHIAN SERIES

General discussion of the series.—The Gamachian series, also of the Cincinnatic system, follows the Richmondian series and has no known

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[16] Whiteaves: Geological Survey of Canada, Palæozoic Fossils, vol. iii, Pt. II, 1895, pp. 111-128.

representative elsewhere in North America. These strata are seen to best advantage at Gamache (or Ellis) Bay, where the characteristic fossils of the series occur in abundance. On Anticosti it embraces all of the Ellis Bay stage, but eventually it may possibly be shown that the upper portion of the Charleton stage should be included in this series. In other words, this Gamachian series is intended to include all American deposits later in age than the youngest Richmondian of Indiana and Ohio and older than the Anticosti series, which in the United States is thought to have its basal equivalent in the typical Medina and Edgewood stages.

Ellis Bay formation (lower half of Richardson's Division C).—The various zones of this formation are best seen about Ellis Bay, at the southwestern end of Anticosti Island. The lowest strata are met with at Junction Cliff, the first prominent cliff to the east of West Point lighthouse, and the higher beds appear in order to Cape Henry, the western point of Ellis Bay. In this bay may be seen the zones from C_5 to C_9. In White Cliff and on the adjacent reef on the eastern side of Ellis Bay may be studied the zones C_6 and C_7, and the succeeding strata come in as one goes eastward to Bear Cliff, the eastern horn of the bay, where the dividing line between C and D is laid at the top of Richardson's C_{11}. These eleven zones of the Ellis Bay formation have a united thickness of 180 feet. They are the eleven lower divisions of C as defined by Richardson; the remaining three higher zones of his C are here referred to Division D. As will be pointed out, the fauna of these higher beds is clearly still Richmondian; but a number of forms are introduced that continue into D and are prophetic of the nearness of Siluric time.

The Ellis Bay formation consists largely of thin-bedded gray limestone with shale partings and distinct zones of shale, particularly in the lower half, in which fine fossils abound. Toward the top the first well developed coral reefs are present—a faunal aspect that often dominates the higher formation.

The zones of Richardson's section, somewhat emended, are as follows:

	Feet
Dinorthis porcata beds (second occurrence).	
C_1 to C_4 or Junction Cliff beds. Lower 20 feet consist of blue shale with thin limestones. There is more shale here than in the upper 40 feet, where the brittle and hard gray to bluish gray limestones with thin shale partings become more prominent...	60
C_5. Ash gray argillaceous limestone interbedded with shale. To be seen just east of Menier's wharf, Ellis Bay, in a small quarry..	6
Parastrophia reversa beds.	
C_6. Ash gray argillaceous limestones and shales......................	20
C_7 to C_8. Ash gray argillaceous limestone with little shale. Below, the beds are of the ash gray color, but at the top they are darker and thinner-bedded. Seen in White Cliff, Ellis Bay...	62

Hormotoma gigantea beds. Feet

C_9. Gray to greenish nodular limestone with greenish shale. Last occurrence of *Beatricea*. Seen on the east and west sides of Ellis Bay, Point Laframboise, and Prinstie Bay of north shore. 12

First marked coral reef beds.

C_{10}. Thin-bedded gray limestones abounding in *Schuchertella pecten*.. 10

C_{11}. Coral reef limestone. Corals in domes up to 3 feet high. Seen at Point Laframboise, Capes Henry and Eagle.................. 10

Zones C_1 to C_5. Junction Cliff or *Dinorthis porcata* beds. The lower 20 feet of this zone abound in *Dinorthis porcata*, with which are associated *Platystrophia biforata* (as in C_6), *Orthis laurentina* (rare, first appearance), *Clitambonites diversus, Leptœna rhomboidalis* (first appearance), *Hindella umbonata* (rare, first appearance), *Atrypa marginalis* (first appearance and rare), *Byssonychia subrecta, Columnaria halli*, and *Protarœa vetusta* (Richmondian form).

From the higher beds, or the upper 40 feet, there are the same brachiopods, but here *D. porcata* is rare and *O. laurentina* is common. *Atrypa marginalis* is also more common, and at the very top becomes the most abundant fossil, a few beds of C_5 being found composed almost wholly of this form.

Zone C_6. Ellis Bay or *Parastrophia reversa* beds. This horizon in the shale beds is profuse in good fossils, of which the following are the more diagnostic forms: *Hindia sphœroidalis, Pasceolus, Stromatopora, Favosites* (?) *gothlandicus, Heliolites* (?) *speciosus, H.* (?) *exiguus, Lingula quadrata, Platystrophia biforata, P.* cf. *reversata* (both species are of the European stock, with odd number of plications on the fold), *Orthis flabellites, O. laurentina, Dinorthis porcata* (rare), *Hebertella maria, Leptœna rhomboidalis, Rafinesquina imbrex, Strophomena fluctuosa, Schuchertella pecten* (first time), *Clitambonites diversus, Parastrophia reversa* (in profusion), *Rhynchonella* (?) *janea, Atrypa marginalis, Hindella umbonata* (greatest abundance), *Byssonychia subrecta, B. superba, Conradella pannosa, Billingsites canadensis*, etcetera.

Zone C_7. Ellis Bay. The fauna has *Pasceolus, Beatricea undulata, Orthis laurentina* (very common), *Hebertella maria, Clitambonites diversus, Leptœna rhomboidalis, Schuchertella pecten, Atrypa marginalis, Hindella umbonata* (small), and *Isotelus* of *susæ* type. At the top of this zone occur the additional forms *Platystrophia* cf. *reversata, P. biforata* (small), *Phylloporina, Encrinurus*, and *Cyphaspis* cf. *girardeauensis*.

Zone C_8. North shore. On the northeast shore at Table Mountain, West Brook of Prinstie Bay, and in the lowest sandstone with nodular shale above at Cape James, there is a coral reef just below the *Hormotoma gigantea* zone of C_9. The chief fossils are *Favosites gothlandicus, Columnaria halli, Calapœcia anticostiensis, Beatricea undulata* (common), *B. nodulosa* (rare), *Orthis* cf. *davidsoni, Platystrophia* cf. *reversata, Schuchertella pecten, Strophomena fluctuosa, Hindella umbonata, Illænus orbicaudatus.*

Zone C_9. South shore. *Hormotoma gigantea* beds. The fossils here are still those found in C_6, but *Beatricea* and *Hindella umbonata* are seen here for the last time. The more characteristic species are *Halysites catenulatus, Heliolites affinis, H. tenuis, Protaræa vetusta, Stromotopora, Favosites gothlandicus, Dinobolus* cf. *davidsoni, Platystrophia biforata, Orthis laurentina* (rare), *Dinorthis porcata, Hebertella maria, Leptæna rhomboidalis, Plectambonites sericeus, Strophomena fluctuosa, Schuchertella pecten, Clitambonites diversus, Parastrophia reversa, Rhynchotrema anticostiensis, Rhynchonella* (?) *janea, R.* (?) *nutrix, Atrypa marginalis, Hindella umbonata* (rare), *Cornulites richmondensis, Subulites elongatus, Hormotoma gigantea, H. rugosa, Salpingostoma richmondense, Cyrtolites desideratus,* and *Ascoceras newberryi.*

Zone C_9. North shore. The fauna here is very much like that of the south shore. The strata may be seen in the back part of Prinstie Bay and in the higher arenaceous limestones of Cape James, lying above the upper sandstone horizon. Some of the species are *Pasceolus halli, Beatricea, Stromatopora, Halysites catenulatus, Heliolites affinis, Columnaria halli, Favosites gothlandicus, Platystrophia biforata, Leptæna nitens* (rare), *Schuchertella pecten, Rhynchonella* (?) *janea, Hindella umbonata* (common), *Cornulites richmondensis, Hormotoma gigantea, H. rugosa,* and *Cyrtolites desideratus.*

The lower zones of C (C_1 to C_8) appear to be represented along the north shore by a thick sandstone showing in many places deposition by agitated waters. The sands are composed of fine quartz and calcite grains, the latter dominating in the upper part where the corals appear. These strata do not have a large fauna except in the higher beds, while some of the lower sandstones show practically no fossils. Above the arenaceous shale forming the base of Point Joseph, at the top of which the line between B and C is drawn, there follows a 15-foot bed of fine grained cross-bedded sandstone and 30 feet of arenaceous shale, which carries the section to the west side of the Bay du Gros Caillou. A concealed area extends the section to the foot of Grindstone Cliff, where an additional thickness of 60 feet of fine grained thin-laminated undulatory sandstone was measured. The above beds contain few fossils. Still higher are other sandstones forming the base of the east end of Cape

James, which are literally filled with large corals and *Beatricea*. Here an additional 40 feet was measured. This gives these lower divisions a thickness of at least 145 feet.

Zone C_{11}. South shore. The lower half of this zone is a coral reef of *Zaphrentis* (8 inches long), *Stromatopora, Favosites gothlandicus, Halysites catenulatus, Heliolites* (?) *exiguus,* and *H.* (?) *affinis.* Above the reef occur *Platystrophia biforata, Clitambonites diversus, Leptæna rhomboidalis, Schuchertella pecten, Parastrophia reversa,* etcetera.

Correlations.—An analysis of the faunules in zones C_1 to C_{11} clearly shows that they have still the Richmondian aspect, for many of the species are derived from Division B. Some of the new forms introduced here as *Dinorthis porcata* (second occurrence), *Leptæna rhomboidalis,* and *Parastrophia reversa* are also of this aspect. On the other hand, a new character is given this higher Richmondian fauna by the appearance of *Stromatopora, Halysites,* a greater abundance of *Heliolites* (?), *Platystrophia biforata* (European stock), *P.* cf. *reversata, Orthis laurentina, O. flabellites, O.* cf. *davidsoni, Schuchertella pecten, Rhynchonella* (?) *janea, Atrypa marginalis,* and *Hindella umbonata*—forms indicating the nearness of Siluric time. No fauna like this is known in the Mississippian sea, and it falls in between the time of the highest Richmondian and the fossiliferous Medina formations of the United States.

The Ellis Bay formation closes the Ordovicic as in general use, or the Cincinnatic as recently defined by the senior author.[17]

SILURIC SYSTEM. NIAGARAN (ANTICOSTIAN) SERIES

General discussion of the series.—Billings, in his work on the strata of Anticosti, drew the line that he thought separated the Ordovicic from the Siluric at the top of his Division B. In the preceding pages it has been shown that all of Richardson's zones, from C_1 to C_{11}, inclusive, retain the Richmondian fauna of Division B, but that to the fauna of these zones are added a number of corals and brachiopods either persisting into the Siluric or forms transitional in development between the Richmondian and Clinton faunas. The Richmondian aspect of the fauna of Division C is clearly maintained throughout to the close of C_9, and even through C_{10} and C_{11}, but in the final 15 feet of the two last named zones nearly all of the Ellis Bay fauna characteristic of this formation vanishes, and only a meager biota of Siluric species persists into the next higher Becsie River formation. The writers have, therefore, removed the greater part of Division C from the Anticosti group as defined by Billings, and drawn

[17] Schuchert: Bulletin of the Geological Society of America, vol. 20, 1910, pp. 487-489.

the line between the Cincinnatic and Siluric periods or systems between Richardson's zones C_{11} and C_{12}.

Becsie River formation (*Richardson's* C_{12} *to* C_{14} *and* D_1).—The Becsie River formation can be seen on the south shore beginning at Bear Cliff and extending eastward to Otter River. The strata here have a thickness of perhaps 200 feet, an estimate which is about 40 feet less than that given by Richardson, this reduction relating entirely to D_1, which Richardson gives as 100 feet. This formation consists of yellowish gray to brown, argillaceous, brittle, nodular and shell limestones, with shale partings, and without zones of conglomerate.

Along the north shore this formation begins at Lousey Cove and forms the line of cliffs and coves extending eastward to Fox Bay. Its upper limit is arbitrarily placed at the east horn of Fox Bay. As will be shown later, the strata of Fox Bay belong to the next succeeding formation. Few fossils were obtained on the north side, as the weather did not permit access to many of the cliffs and much is concealed in the upper half, but the thickness is probably slightly in excess of 200 feet. The zones of the Becsie River formation are characterized as follows:

Phænopora expansa beds. Feet

D_1 (Richardson's C_{12}). South shore. Gray limestones with argillaceous partings 62

Has *Brachyprion leda, Schuchertella pecten, Parastrophia* n. sp. 1 (transitional between *P. reversa* and *Clorinda barrandii*), and *Atrypa marginalis.*

D_2 ($=C_{13}$). South shore. Brownish gray, argillaceous, brittle, nodular limestones, interstratified with thin shale bands. Forms Bear Head 42

Has *Stromatopora, Favosites gothlandicus, Rhipidomella circula* (a Clinton species), *Brachyprion leda, Parastrophia* n. sp. 1, *Clorinda* n. sp., *Atrypa marginalis,* and *Anoplotheca planoconvexa* (common, the Dundas, Ontario, Medina form).

D_3 ($=C_{14}$). South shore. Brownish gray thin-bedded limestones forming outer beds of Long Point.......... 35

Has *Stromatopora, F. gothlandicus, Phænopora expansa* (common), *Rafinesquina ceres* or *profunda,* and *Parastrophia* n. sp. 1.

Clorinda barrandii beds.

D_4 ($=D_1$). South shore. Thin-bedded grayish to brownish gray somewhat arenaceous limestone with almost no shale partings. Richardson gave the thickness as 100 feet, but there is believed to be little more than.......... 60

These beds may be seen between Long Point and Whale Cliff, and especially at Becsie River and Duck River. All of the strata have *Clorinda barrandii,* but they are especially abundant in the lower 30 feet. The higher 20 feet are marked by an abundance of *Phœnopora expansa*. Other common fossils are *Stromatopora* (very common), *Halysites catenulatus*, *Favosites gothlandicus*, *Eridophyllum* cf. *rugosum*, *Heliolites exiguus*, *Pachydictya* cf. *obesa* (very common), *Orthis flabellites*, *Schuchertella pecten*, and *Conchidium* n. sp.

Correlation.—The meager fauna of zones D_1 to D_4 is unlike any other American late Ordovicic or early Siluric assemblage. Of the previous or Ellis Bay fauna very little remains in these zones other than the corals and a few long enduring brachiopods. The new or migrant forms are Siluric in aspect, as *Phœnopora expansa*, *Pachydictya* cf. *obesa*, *Rafinesquina profunda* (a later development of the earlier *R. ceres*), *Orthis flabellites*, *Schuchertella pecten*, *Anoplotheca planoconvexa*, *Clorinda barrandii*, and the transitional forms between *Parastrophia reversa* and *Clorinda barrandii*. Why the Richmondian fauna so largely dies out in the upper part of the Ellis Bay formation and only a few forms continue into the Becsie River formation is not clear. It is true that the physical environment in the two formations as observed along both shores was slightly different, there being more shale in the lower formation. This no doubt had its influence in eliminating and introducing new forms, but it is not thought to have been the major cause of the rather marked change in the faunas. One is therefore compelled to look elsewhere for the explanation of this faunal change. That somewhere there was a physical change of great importance is seen in the diminished fauna and in the gradual introduction of new migrants. This physical change is believed to have been caused by the mountain-making movements closing the Cincinnatic period, producing here a different depth of water as indicated by the greater importance of limestone deposition and probably a different alignment to the Poseidon (North Atlantic) currents. For these reasons the writers feel justified in beginning the Siluric period as here delimited. This divisional line is, of course, a somewhat arbitrary one, as there is no apparent break here in sedimentation, nor is there a particularly marked change in the character of the deposits. The evidence is, therefore, wholly of a faunal character, reflecting important physical events going on elsewhere.

In this connection the authors wish to emphasize the marked differences in the faunas of the Ellis Bay and the Becsie River formations. In the former the unmistakable Richmondian aspect is maintained to the end, although there is a great dying out of species in the final 15 feet. Some species continue into the Becsie River and later formations, but the number is probably not greater than six or seven, and these are not typical Richmondian species, but rather Siluric forms. On the other side, the Becsie River deposits often abound in fossils, and yet the species are few in number and all are Siluric in aspect. The writers realize that such differences in the faunas are most readily explained by assuming a time break between the Ellis Bay and the Becsie River formations and that the latter rests disconformably on the former. At the time these field studies were made, no physical evidence of an hiatus was observed, but it may be that such actually exists. Such contacts are very easily passed over, and especially when one accepts the conclusion of Billings and Richardson that the entire Anticosti strata represent an unbroken series beginning in the early Richmondian and continuing well up into the Siluric. On the other hand, the appearance of the yellowish gray to brown brittle limestone characterizing this formation, and occurring at various levels from A to E, is always accompanied by a sparse fauna. At the top of Junction Cliff this type of limestone is marked by *Atrypa marginalis* almost alone, and such may be in part the explanation for the faunal change at the base of the Becsie River formation.

The nearest approach to the faunas of zones D_1 to D_4 are those of the sandy strata referred to the Clinton and occurring at Dundas, Flamborough Head, Thorold and Hamilton, Ontario, and in the lower thin-bedded arenaceous shales of the upper Medina of the Niagara River gorge at Evans Gully. At the latter place these strata are always regarded as of the upper Medina, but in a distance less than 30 miles to the northwest the identical horizons are referred by Logan[18] to the Clinton. The thickest section is near Dundas and measures about 100 feet in depth, a development in harmony with the upper Medina of the Niagara River gorge. In the lower 10 feet just above the "gray band" occur, near Dundas, *Zaphrentis stokesi, Helopora fragilis, Pachydictya crassa, Phænopora ensiformis, Rhinopora verrucosa, Leptæna rhomboidalis, Schuchertella pecten, Dalmanella elegantula, Rhynchonella* (?) *neglecta, Anoplotheca planoconvexa, Whitfieldella naviformis, Atrypa reticularis, Spirifer radiatus, Modiolopsis orthonota, Murchisonia* (?) *subulata*, and *Encrinurus punctatus.* In higher strata occur the same species, especially the typical Medina forms, but *A. planoconvexa* is restricted to the lowest beds.

At Hamilton, Ontario, the senior author has gathered the identical fauna in the so-called Clinton beds, here having *Arthrophycus harlani,* and again, but in fewer species, in Evans Gully, near Niagara Falls, in a zone 25 feet thick above the heavy bedded sandstone making here the

[18] Logan: Geology of Canada, 1863, pp. 312-315.

base of the upper Medina. Beneath the last are the red marls of the lower Medina. There can be no doubt that at all of these places we are dealing with the basal beds of the upper Medina.

From these statements it is seen that the upper Medina, which is now commonly referred to as the typical Medina, includes beds that are clearly Siluric, and in time not far removed from the Clinton. The Medina fauna has three or four species that are seen only in the Becsie River formation, while some of the other forms first appear in the succeeding beds. Nevertheless, there is very little in common between the Medina and the Becsie River formation. Until the faunas of these four zones have been completely studied a more detailed correlation can not be made. It is thought, however, because of the absence of *Spirifer radiatus, Atrypa reticularis, Dalmanella elegantula,* and *Encrinurus punctatus* in the Becsie River formation, that it is older than the upper Medina.

A somewhat similar fauna occurs in the Edgewood formation of Illinois and Missouri.[19] So far as known, these species are *Stromatopora, Zaphrentis, Calapœcia canadensis, Lyellia thebesensis, Clathrodictyon vesiculosum, Favosites* cf. *asper, Halysites, Tentaculites incurvus, Lingulops, Dalmanella* cf. *meeki, Orthis* cf. *callactis, Leptæna rhomboidalis, Rafinesquina mesacosta, Schuchertella missouriensis, Rhynchotrema* cf. *inæquivalvis, R.* cf. *dentata, R. janea, Rhynchotreta thebesensis, Triplecia* n. sp. (plicate type), *Clorinda, Atrypa marginalis, A. putilla, Spirifer* cf. *sulcatus, Hindella* (?) *billingsana, Cypricardinia* cf. *arata, Conradella* cf. *dyeri, Encrinurus, Proetus determinatus, Lichas clintonensis,* and *Homalonotus.* The time of this fauna may be that of the zones D_1 to D_4, but it is evident that the source of this life is not that of the North Atlantic, for genera are seen here unknown in the Becsie River formation.

Gun River formation (Richardson's Division D, excepting D_1).—The Gun River formation, as exposed on the south shore, consists essentially of ash gray to yellowish white limestone (the bituminous limestones of Richardson, Geological Survey of Canada, 1857, page 301), usually in thin beds interstratified with but little shale. Coral reefs are a marked feature of the lower half of this formation, and with them intraformational conglomerates are often associated. Thin zones of conglomerate consisting of small flat pebbles lying horizontally in a limestone matrix are also common, particularly in the upper portion. The thickness of the formation is about 400 feet. The strata on the south shore may be seen from Saint Anns Cliff to within one mile of Jupiter River. Excel-

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[19] Schuchert: Journal of Geology, vol. 14, 1906, p. 728.

lent sections may be obtained at the type locality where Gun River flows across the strata.

On the north shore this formation may be seen from Wreck Beach to East Cliff, where excellent sections are obtainable. Here considerable shale is present in the lower part of the formation and a fauna different from the equivalent beds of the south shore. The higher strata are more calcareous and have more coral reefs than those of the south shore.

The detail of the various beds is as follows:

Hyattella congesta beds. Feet

D_5 (= D_2–D_3). South shore. Ash gray to yellowish white thin-bedded limestones abounding in corals and intraformational conglomerates 70

These zones may be seen to best advantage at Saint Marys, Saint Anns, and in the lower portion of Hannah Cliff. The more common fossils are *Stromatopora*, *Favosites gothlandicus*, *F. venustus*, *Halysites catenulatus*, and *Conchidium*.

D_6 (= D_4). South shore. Pinkish gray limestones with thin shale partings and local coral reefs 60

These beds may be seen at the top of Hannah Cliff and eastward to 3 miles west of Gun River. Of fossils there are *Stromatopora*, *Favosites gothlandicus*, *F. venustus*, *Heliolites affinis*, *H. exiguus*, *Zaphrentis* (?) *pygmæa* (very small, in greatest profusion), *Rhipidomella* cf. *circula*, *Rafinesquina profunda* (very common), *Rhynchonella bidens* (abundant), *R.* cf. *glacialis* (common), *Hyattella congesta* (first appearance at base of this zone in small specimens), *Whitfieldella* (small), *Platyceras* cf. *niagarense*, *Calymene* cf. *vogdesi* (large), and an abundance of small ostracoda.

D_6. North shore. On the west side of Fox Bay and on the east side at Reef Point this zone is to be seen. At Reef Point *Heliolites exiguus* is extremely common. At the other place were collected *Orthis flabellites*, *Schuchertella pecten*, and *Hyattella congesta*.

D_7 (= D_5–D_6). South shore. Same character of strata as before. Seen about Gun River and to the west and to the east of this river for 2 miles 113

Same corals as before. *Pasceolus*, *Semicoscinium*, *Phænopora expansa*, *Helopora fragilis*, *Pholidops ovata* (exceedingly abundant), *Orthis flabellites*, *Rafinesquina profunda*, *Schuchertella pecten*, *Rhynchonella bidens*, *Hyattella congesta*, *Leperditia* (large), and *Illænus*.

D_7. North shore. These zones of the south shore are here developed under different physical conditions and have a resulting different faunal assemblage. On the south shore the habitat was one of limestone, while on the north shore the environment was

Feet

one largely of muddy bottoms. The fossils are plentiful and in excellent preservation on Wreck Beach, the Gull Cape of Richardson. The section here beginning at the base is as follows:

Rhynchonella fringilla-glacialis beds.

Blue to gray shale with thin gray limestones	50
Brownish gray nodular thin-bedded limestones	20
Thick-bedded gray limestones with some corals	40
Thin-bedded limestones and shales	30

The shale zone or lower 50 feet has an abundance of *Alveolites labechi, Favosites gothlandicus, F.* cf. *favosus, Rafinesquina profunda, Schuchertella pecten, Rhipidomella* cf. *circula, Rhynchonella glacialis, R. fringilla* (both species are prolific).

From the limestone series are recognized *Favosites gothlandicus, Climacograptus* n. sp., *Brachyprion leda, Rhipidomella circula,* and *Rhynchonella bidens.*

D_8 ($=D_7$–D_8). South shore. Gray and light blue thin-bedded limestones and conglomerates with small flat pebbles in limestone matrix. Seen at Cape McGilverey 65

The more common fossils are *Pasceolus, Heliophyllum* (6 inches long), *Favosites gothlandicus, F. venustus, Halysites catenulatus, Climacograptus* cf. *ulrichi, Helopora fragilis, Schuchertella pecten, Triplecia ortoni* (first appearance and rare here), *Stricklandinia lens* (first appearance and rare here), *Atrypa reticularis* (first time), *Hyattella congesta* (also the var. *quadricostata*), *Rhynchonella bidens,* and small ostracoda (common).

D_8. North shore. These zones are well exposed in the cliff west of Sand Top Bay. Here there are 150 feet of limestones and shales. Between these strata and those of Wreck Beach there is a concealed zone in which 50 to 70 feet of strata may be hidden. The recognized fossils are *Pasceolus, Favosites* cf. *favosus, Rhynchonella fringilla* (very rare), and *Stricklandinia lens* (common).

D_9 ($=D_9$–D_{10}) or *Triplecia ortoni* beds. South shore. Ash gray to reddish gray thin-bedded limestones weathering to yellowish brown but generally whitish 92

Seen from 2½ miles west of Jupiter River to near the Jupiter River Cliff. The fauna here listed is from the lower 65 feet and the specimens are excellent. Among them are: *Bilobites bilobus, Hebertella fausta* ?, *Leptæna rhomboidalis, Plectambonites* n. sp., *Schuchertella pecten, Triplecia ortoni* (common, a variety of the Ohio form), *Pentamerus* cf. *oblongus* (an elongate early form), *Clorinda* n. sp. (not *fornicata*), *Atrypa* cf. *rugosa, A. reticularis, Anoplotheca hemispherica* (first appearance), *Nucleospira* n. sp. (also in E_3), *Platyceras niagarense, Illænus* cf. *daytonensis, Acaste orestes, Cheirurus nuperus* ?

Feet

D_9. North shore. The equivalent of these zones is seen to great advantage at East Cliff, where about 150 feet of limestone with some shales occur.

The lower 30 feet of this section is a coral reef of corals and coral conglomerate, with some nodular limestone. These strata also make up the submerged East Cliff reefs, and because of their very rough character are very dangerous to navigation. The fossils are essentially corals—*Stromatopora*, *Favosites gothlandicus* (mural pores seen), *F. favosus*, *Strombodes diffluens*, *Eridophyllum* cf. *multicaule*, *Halysites* 2 species, *Platystrophia biforata* (same in C_6), *Leptæna rhomboidalis*, *Schuchertella pecten*, *Pentamerus oblongus* (rare), *Rhynchonella bidens*, *Atrypa reticularis*, *Anoplotheca hemispherica*, and an abundance of ostracoda.

The coral reef is followed by about 10 feet of blue limestone with shale partings, above which are 40 feet of granular limestones also with shale partings. Here the corals are rare and do not make reef limestone. Slabs are covered with small bryozoans and Clinton ostracoda. Other fossils are *Rafinesquina profunda*, *Brachyprion leda*, *Schuchertella pecten*, *Rhynchonella bidens*, *Atrypa reticularis*, *Anoplotheca hemispherica*, *Homœospira* n. sp., *Hyattella congesta*, and *Stricklandina lens*.

The above zone is followed by another that may be called the *Hyattella congesta zone* because of the abundance and large size of this brachiopod. The lower 35 feet are bluish gray thin-bedded nodular limestone with shale partings, followed by 10 feet of granular shell or pentameroid limestone. The more common fossils are *Favosites gothlandicus*, *Heliolites exiguus*, *Cornulites*, *Plectambonites transversalis*, *Brachyprion leda*, *Rhynchonella bidens*, *Atrypa reticularis*, *Hyattella congesta* (very common in the lower 35 feet and rare in the upper 10 feet, where the shell is seen for the last time), *Stricklandinia lens*, *S. lirata*, and *Pentamerus oblongus* (the pentameroids here becoming very abundant).

The highest strata of East Cliff are 30 feet of grayish brown nodular limestone with fewer fossils, followed by the terminating 10 to 15 feet of gray to white shell limestone abounding in the pentameroid *Stricklandinia lens*. Other fossils are *Rafinesquina profunda*, *Orthis flabellites*, *Atrypa reticularis*, *Anoplotheca hemispherica*, and *Tremanotus*.

Correlation.—An inspection of the fossils cited in the various beds of the lower part of the Gun River formation (*Hyattella congesta* beds) will show that the fauna clearly has the impress of "Clinton" time, using this term in the widest sense. This is seen in the following species: many of the corals, *Phænopora expansa*, *Helopora fragilis*, *Rhipidomella* *circula, Orthis flabellites, Rafinesquina profunda, Rhynchonella bidens, Stricklandinia lens, Atrypa reticularis* (first appearence), *Hyattella congesta, Platyceras,* and *Calymene* cf. *vogdesi.* However, when one attempts to correlate this zone with any of the Clinton formations of the United States difficulties at once beset the comparisons, because the lower Gun River fauna is a generalized assemblage, having species that are restricted either to the Appalachian area, western New York, or the Ohio region.

The same generalized Clinton assemblage also marks the upper Gun River in the *Triplecia ortoni* beds. Here the New York, or Appalachian, species, *Rhynchonella bidens, Stricklandinia lens, Pentamerus oblongus* (first appearance in this zone, and then remains throughout the higher beds to the end of E), *Anoplotheca hemispherica* (same range as last species), and *Hyattella congesta,* are associated with *Triplecia ortoni.* The latter, elsewhere than Anticosti, is only seen in the region of the Cincinnati axis from Ohio to Oklahoma, and in Alabama, where it occurs underneath the Rockwood Clinton.

The Ohio Clinton is devoid of *Pentamerus oblongus, Atrypa reticularis,* and *Anoplotheca hemispherica,* brachiopods unknown in the lower Gun River formation. If these are reliable time indicators, then it may be said that the Ohio Clinton holds about the time of the lower Gun River and that in the south *Triplecia ortoni* appears in profusion earlier than on Anticosti, as here this form is not common until in upper Gun River time. If, on the other hand, it is held that the guide fossils appear somewhat earlier on Anticosti, then the Ohio Clinton would seem to hold the time of D_9 of the Gun River formation up to the top of E_3 of the Jupiter River formation. *Triplecia ortoni* ranges here through 279 feet of strata, whereas along the Cincinnati axis this form is apparently restricted to less than 25 feet of limestones.

The lower fossiliferous Clinton of the Rochester, New York, region (Wolcott limestone) appears not to be older than the upper Gun River, for the diagnostic fossils *Bilobites bilobus, Pentamerus oblongus, Atrypa reticularis, Rhynchonella bidens, Hyattella congesta,* and *Anoplotheca hemispherica* are common to both formations.

It appears probable that some of the diagnostic Clinton fossils appear earlier on Anticosti than in the United States. This seems to be true for *Hyattella congesta, Stricklandinia lens, Pentamerus oblongus, Rhipidomella circula, Anoplotheca hemispherica, Atrypa marginalis, A. reticularis,* and some of the corals. It is this that leads the writers to correlate the Clinton formations of the United States with apparently somewhat later similar faunal occurrences on Anticosti.

For the present it can only be stated with some degree of probability that the Clinton faunas begin to appear in the lower Gun River formation and then continue throughout the Jupiter River division, and gradually take on more and more of the characters of the Irondequoit or highest reef Clinton, an aspect which is not fully attained even at the top of Division E, where *Anoplotheca hemispherica* is in greatest development. If, on the other hand, one uses the occurrence of *Monograptus clintonensis* and *Spirifer radiatus meta* as the guide for correlation, then the higher Clinton of New York and the northern Appalachians holds the time of the higher zones of the Jupiter River formation—that is, from E_3 to E_9. It is therefore concluded that the New York Clinton begins later than the lower half of the Gun River and that the higher Clinton (Williamson and Irondequoit) correlates best with the zones above E_5 of the Jupiter River formation.

Jupiter River formation (Richardson's Division E).—The strata of this formation are best seen beginning at the high cliff on the west side of Jupiter River (hence the name for the division) and thence eastward to the Jumpers. The thickness of these beds is 561 feet, which in the main are thin-bedded light colored limestones interstratified with shale partings. The lower 100 feet are green shales followed by a similar thickness of argillaceous limestones above which the limestones are purer. No intraformational conglomerates were seen in this formation.

The formation is again seen along the southeastern shore of the island from Heath Point westward to Pavilion River. These deposits are probably those of somewhat deeper and certainly of clearer water, with fairly uniform physical conditions, seen in the fact that the strata here are more uniformly limestones in which corals, coral reefs, and large brachiopods (*Pentamerus oblongus* chiefly) abound. The thickness of these eastern Jupiter River equivalents has not been ascertained. The strata are nearly horizontal and undulating. It is believed, however, that their thickness fully equals that of the western exposure.

According to Richardson's section the zones along the southwestern shore of the island are as follows:

Triplecia ortoni beds—continued.

	Feet
E_1. Not seen	27
E_2. Light green argillaceous shales. Finely exposed in the lower part of West Cliff of Jupiter River. Only fossil seen is *Atrypa reticularis.* Richardson's estimate of thickness is 60 feet, the authors'	80
E_3. Light drab argillaceous limestones. Strata much jointed, in which the fossils are often excellent, but scarce. They are *Mono-*	

Feet

graptus clintonensis (common), *Mesograptus, Bilobites bilobus, Brachyprion leda, Schuchertella subplana, Triplecia ortoni* (rare), *Clorinda* n. sp., *Zygospira* cf. *modesta, Atrypa reticularis, Anoplotheca hemispherica, Spirifer radiatus meta, Nucleospira* n. sp., *Clionychia nitida* (common), *Oncoceras futile, Platyceras* cf. *niagarense* (small), *Calymene vogdesi* (3 inches long, same in Clinton of Ohio and New York), *Illænus* (large new species), *Acaste orestes, Encrinurus punctatus* ?, *Lichas* cf. *boltoni* 80

Oncoceras futile beds.

E_4. Same limestones as E_3, but gradually passing into purer limestone. Fossils the same as in E_3, but without the graptolites......... 22

E_5. Ash gray, hard, conchoidally fracturing, thin-bedded limestones abounding in *Oncoceras futile.* Other fossils are *Favosites gothlandicus, Atrypa reticularis, Anoplotheca hemispherica* (large and lamellose here), *Stricklandinia lens, Clionychia nitida, Calymene* cf. *vogdesi*, and *Acaste orestes*..................... 43

Stricklandinia lens beds.

E_6 and E_7. Same petrographic character as below. *Stricklandinia lens* in profusion. Otherwise the fauna is that of below........... 13

E_8 and E_9. Same petrographic character as below. The common species here are *Favosites gothlandicus, Monograptus clintonensis*, many bryozoa, *Dalmanella elegantula, Orthis flabellites, Brachyprion leda, Clorinda* n. sp. (same in D_9), *Stricklandinia lens* (rare here), *Pentamerus oblongus* (rare), *Atrypa reticularis, Anoplotheca hemispherica*, and *Acaste orestes*........... 138

E_{10}. Measures largely concealed.

At the Jumpers, 2 to 3 miles east of Southwest light-house, the terminal 20 feet of this zone may be seen abounding in fossils—one of the richest localities on the island—but the variety is not so large. Some of the fossils are *Favosites gothlandicus, F. venustus, Plectambonites transversalis, Leptæna julia, Brachyprion leda, Strophonella geniculata* Shaler (not Hall), *Stricklandinia lirata, S. brevis, Pentamerus oblongus, Anoplotheca hemispherica, Spirifer radiatus meta, Leperditia* (very large), *Acaste orestes, Calymene vogdesi*............... 158

Correlation.—The Jupiter River faunas are clearly of Clinton aspect, retaining at the base the Ohio or older phase derived from the preceding Gun River formation, while the higher strata, with their abundance of *Pentamerus oblongus*, are clearly related to the New York Clinton. This correlation is further strengthened by the fact that the life of the following Chicotte formation is in harmony with the northern Niagaran faunas of the upper Mississippi Valley.

In this correlation there are seen certain peculiar and divergent faunal elements. For instance, in the Williamson division of the New York Clinton, *Hyattella congesta* characterizes this zone, but on Anticosti this species is at home during an earlier time in the lower Gun River formation, and it is not known at all in the Jupiter River deposits. Coral reefs in the Mississippian sea are not prominent until long after the introduction of the Niagaran, but on Anticosti the coral reefs dominate all Anticostian time. *Pentamerus oblongus* appears in the Gun River deposits long before it is seen in New York. *Anoplotheca hemispherica* appears near the top of the Gun River deposits, and thence continues to the very top of the Jupiter River, thus ranging through 650 feet of calcareous deposits.

Chicotte formation (*Richardson's Division F*).—This series of limestones is strikingly different from any of the preceding in that they are more heavily bedded, have almost no shale partings, and are white and coarsely granular, due to the crinoidal pieces, corals, and *Stromatopora* of which they are mainly composed. The contact with the Jupiter River formation is abrupt and there appear to be no transition beds between them. The total thickness is about 70 feet.

These limestones are well displayed at Southwest Point, where they are decidedly undulatory, and recur at intervals eastward to Pavilion River. The most continuous section was seen at the type locality for the formation in the cliffs westward from Chicotte River, where the beds are more undulatory than elsewhere. The zones are as follows:

	Feet
F_1 and F_2. Gray slightly granular limestone with green shale partings.	18
Seen at the Jumpers and Chicotte Cliff. At the eastern end of the section these zones include Stromatopora reefs. Corals are common as *Stromatopora*, *Favosites favosus*, *F. gothlandicus*, *F. venustus*, *Alveolites labechi*, *Heliolites exiguus*, *Ptychophyllum canadense*, and *Ormoceras canadense* (*Huronia vertebralis*).	
F_3 and F_4. White granular crinoidal limestone in beds from 6 to 18 inches and without shale partings..........................	55
Has *F. favosus*, *Orthis flabellites*, *Leptæna rhomboidalis*, *Atrypa reticularis*, *Cyrtia myrtea*, *Spirifer radiatus*, *Phragmoceras* (small). Very large crinoid stems occur, possibly of *Crotalocrinus*.	

Correlation.—The fauna of the Chicotte formation is as yet a small one and there is little on which to base positive correlations. Most of the species are those of the lower horizons, while the new elements in the crinoidal life are so comminuted that nothing can be made of it. It seems to correlate best with the highest zone of the western New York Clinton, the Irondequoit, an horizon now regarded as the transition zone to the Rochester shales.

The Anticosti section ceases with the Chicotte formation and younger Siluric beds are unknown in the northern region of the Gulf of Saint Lawrence. Later beds are known farther south along the north shore of the Bay de Chaleur and at Arisaig, Nova Scotia.

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SOME EFFECTS OF GLACIAL ACTION IN ICELAND[1]

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Introduction

The dominant geological features of Iceland are its glaciers and its volcanoes, both of which are developed on a tremendous scale and afford unusual opportunities for detailed study. The island itself is essentially an uplifted plateau country, averaging 500 to 700 meters in elevation, and consisting in large part of basaltic lava flows and associated tuffs and breccias. Fringing this plateau at different points are lowland coastal strips, whose total area is nearly one-fifteenth of that of the entire island; to these all habitation is practically confined, the rest of

[1] Manuscript received by the Secretary of the Society September 21, 1910.

the island being a barren waste of lava and glacial debris, devoid of forests, and even vegetation, and worthless from an economic standpoint, but valuable to the geologist because of its excellent exposures.

Soundings by the Danish government have shown that these lowland coastal areas, in north and west Iceland especially, extend seaward as a coastal rock shelf 100 to 200 kilometers out from the shore; in this shelf, old valleys, 60 meters deep and of typical river valley features, have been treated as continuations of the present fiords. According to Thoroddsen,[2] this continental shelf was cut in late Miocene or Pliocene, when all Iceland was uplifted; it was submerged at the close of the Pliocene. This proof, that the present fiord valleys are old river valleys modified by ice action during the Glacial epoch, is an important fact bearing on the physiographic development of this region.

During the Glacial epoch all Iceland was covered by an ice-sheet, which moved from the center of the island oceanwards and profoundly altered the physiographic aspect of the land surface. Remnants of this ice-cap still remain and occupy considerable areas in the interior plateau, Vatnajökull covering over 8,500 square kilometers and Hofjökull and Langjökull each about 1,300 square kilometers.

Since the recession of the ice, the land surface has been altered very slightly by water erosion, and, in north Iceland especially, has remained practically as the ice left it. There the bedrock is the basalt formation, which consists of a series, over 1,000 meters thick, of nearly horizontal lava flows with intercalated tuff beds. This formation is fairly uniform and free from elements which might tend to disturb the normal development of the physiographic features characteristic of either ice or water action; its material is, moreover, peculiarly adapted to retain the finer markings produced by an erosive agent. Such a combination of fortunate conditions is unusual, and renders this country specially suitable for the detailed study of the land forms resulting from glacial sculpture.

Two groups of such features of mountain glaciation, in particular, attracted my attention during a short trip across the island in August, 1909; these were: (*a*) the glacial modeling and sculpture of preexisting river valleys during the period of maximum ice development, or ice-flood period, as E. C. Andrews and others have named it; (*b*) the effect of the surface of the ice-sheet as a plane of reference toward which the upland surfaces tended to be beveled. My time was unfortunately limited, and the impressions recorded in the following paragraphs are intended

[2] Island, Grundriss der Geographie und Geologie, von Prof. Dr. Th. Thoroddsen, Peterman's Mitteilungen. Ergänzungsheft. 152, 1906, pp. 93-98.

rather to direct attention to the phenomena than to present a finished study of the same.

Features of Valley Glacier Erosion

ICE AS AN EROSIVE AGENT

During the Glacial epoch the old river valleys were completely filled with ice, the flow of which, notwithstanding its general resemblance to that of water, differs from the latter with respect to its greater viscosity or plasticity, whichever term describes the case more correctly. Ice is therefore a correspondingly stiffer or less pliable and delicate tool; it is a more conservative and stubborn erosion agent than water, and shifts its direction less readily. It works on a large scale, filling the entire valley, and tends during its period of rapid cutting to smooth out the little irregularities of the river valley and to truncate and align all projecting and overlapping spurs; in short, to simplify the general shape of the valley and to emphasize its symmetry, with the result that the eye takes in long stretches of the glaciated valley at a glance and at the same time is impressed with the unity and dignity of the whole. Glacial valleys, with their open vistas and majestic curves, possess a charm and an individuality that is unique and characteristic.

The flow of ice through a valley is controlled and directed by the valley walls and floor; they prescribe, in a measure, the lines along which the ice must work; and, in turn, they suffer profound modification. These relations between ice-flow and valley shape are so definite that it is possible to predict the changes which an eroding ice current or stream would make in the configuration of a given river valley. In an ice current filling a valley, as in a river, the rate of flow is generally greatest at a point midstream and near or at the surface, while the points of most intense ice action (abrasion and plucking) are on the valley bottom and the adjacent lower slopes, as there the pressure is greatest and the flow sufficient to carry off the debris from the powerful chiselings of the ice. The erosive action of an ice current is concentrated, therefore, along the valley floor and lower slopes. During the period of maximum ice erosion, the valley bottoms were often cut down far below the baselevel and now appear as basins filled with glacial rock material.

THE ICE-FLOOD PERIOD

The Glacial epoch was a period of ice-flood and of torrential ice action, when prodigious feats of erosion were accomplished, far beyond the powers of the relatively stagnant glaciers of today. The present epoch is one of ice drought, and the erosive action of the glaciers during the two periods is, therefore, not comparable. This Mr. E. C. Andrews has clearly demonstrated in his paper, "Ice-flood hypothesis of the New Zealand sound basins,"[3] in which the effects of the two stages are strongly contrasted and likened directly to those of water action during times of flood and of drought, the flood period in the river bed or glacial valley being one of intense corrasion and down-cutting, the drought period one of stagnation and aggradation.

The features which Mr. Andrews declares characteristic of intense ice action in New Zealand occur also in Iceland, though in somewhat different form, as might be expected from the differences in bedrock and thickness of ice-cap in the two countries. In New Zealand, as in southeastern Alaska, the mountain uplands average from 1,500 to 2,000 meters in elevation, while in Iceland the plateau country rarely reaches 800 meters. As the upland areas in both cases were covered by an ice-sheet, the depth of the ice currents in the valleys was far greater in New Zealand and Alaska than in Iceland, and their cutting action consequently much more profound. The double cliff slopes which occur frequently in New Zealand and also in Alaska, and which evidently are marks of the most intense glacial corrasion, were rarely seen in Iceland. The "through" valleys of Professor Tarr, which are common in Alaska, are seldom found in Iceland. Hanging valleys, vertical cliff bases and truncation of spurs, on the other hand, physiographic forms which are considered special marks of intense glacial action in New Zealand, are abundant in Iceland, as well as other features, which may be noted briefly.

FEATURES RESULTING FROM THE ACTION OF A SINGLE VALLEY GLACIER

The master valleys in north Iceland, as Eyjafjardardalur, Fnjoskádalur, Fljotsdalur, and others, exhibit: (*a*) U-shaped, troughlike cross-sections; (*b*) hanging side valleys; (*c*) sharp steepening of grade at the valley head, due in part to cirque action, but also probably in part to ice currents, which on the advance of the ice-sheet from the interior oceanwards were deflected by the directive influence of the existing valleys, and, plunging into the valleys at their head, tended to abrade with special severity there. During the period of maximum ice action, the grade of the valley floor below the valley head was greatly decreased and occasionally reversed for short distances, as indicated by the present hollows at such points; (*d*) glacial grooves and markings along the valley

[3] Journal of Geology, xiv, 1906, pp. 22-54.

sides; (*e*) alignment and straightening of valley sides by truncation and removal of projecting and overlapping spurs; (*f*) valley sides, occasionally terminating in vertical cliffs; (*g*) absence of talus slopes at base of cliffs; (*h*) flat open valley floors now usually covered with débris, left by receding glaciers and worked over to some extent, at least, by subsequent stream action. Occasionally low rounded knobs of bedrock project above the valley bottom, but are not of sufficient size or frequency to disturb its general aspect.

FEATURES DEVELOPED AT JUNCTIONS OF TRIBUTARY GLACIERS WITH TRUNK GLACIER

Hanging valleys.—At the points of confluence of tributary valleys with the main valley, different physiographic effects occur, dependent on the relative size of the two valleys and on their angle of confluence. Small ice-tongues, entering the main valley at large angles, were undercut by the master ice-stream, which left their valley floors perched or hanging at different elevations along the sides of the main valley; waterfalls emphasize still further the sites of such hanging valleys, and are so plentiful in Iceland that the traveler is rarely out of sight of one or more; in most cases water erosion at such points has been slight, and small notches only have been cut in the lips of hanging valleys since the recession of the ice.

Glacier junction basins.—Larger ice-streams, confluent at wide angles and yet able, practically, to hold their grade with that of the trunk glacier, tended to widen and overdeepen the main valley at the point of union; there the valley grade was frequently reversed for a short distance with resultant formation of rock basins, now filled with glacial material. When several such converging valleys entered the main valley on opposite sides, a wide, open amphitheater was formed, which for impressiveness and dignity far surpasses any feature of ordinary river valleys. Eyjafjardardalur is especially noteworthy because of such valley junctions.

Glacier junction spurs.—In the case of two large glacial valleys confluent at acute angles, characteristic, low junction spurs, attenuated by the overriding ice-masses to elongated shapes, rounded in cross-section and almost cigar-shaped in plan, were usually formed. These *glacier junction spurs,* as they may be called, are a distinctive feature of certain glacial valleys and merit a brief word of description. The normal tendency of intense glacial cutting in valleys is to truncate and even to remove all projecting spurs which lie in the path of the advancing ice-flow and to align their bases. In the case of glacier junction spurs, however, the direction of the spur itself practically coincides with that of the ice-flow. Under these unique conditions the sides of the spur are not only aligned in both valleys, but its ridge is greatly reduced and ground down by the confluent overriding ice currents. After recession of the ice, it appears as a low, gently sloping, drawn-out tongue of bedrock pointing downstream and separating the two valleys to their very junction, where it passes into the valley floor. At the same time its effect is to merge the two valleys and to render their junction less abrupt. In case this type of glacial junction spur occurs between fiord extensions of glacial valleys, it reaches out as a low, gently sloping peninsula, and finally passes beneath the water. Occasionally a series of small islands, each elongated in the direction of ice-flow, appear, and are simply the higher parts of the continuation of the junction ridge under water, as indicated by soundings. On passing inland, these glacier junction spurs or ridges rise gradually and increase in width until finally their slope becomes abruptly steeper and leads, then, rapidly up the main mountain mass. The decrease in the slope of the ridge of a glacier junction spur toward its seaward tip is characteristic. The crest itself is not always a smooth line, but is usually undulating and irregular after the manner of hummocky glaciated rock floors. Such glacier junction spurs are typically developed between Fljötdalur and Laxárdalur, in north Iceland, and between the converging branches of the Hvitá, in Myrar, west Iceland.[4] In southeastern Alaska they also occur frequently, notably near the head of Lynn Canal, at the junctions of Taiya, Chilcoot, and Chilcat inlets.

Glacier junction deposits.—At the junction of all large tributary valleys, the normal flow of the trunk glacier is more or less disturbed; jamming of the ice results, and produces deflection and stoppage of subglacial drainage, conditions to which peculiarly shaped gravel deposits and mounds, as well as the irregular valley bottom at such points, now bear witness. In Laxárdalur, Adalreykadalur, and Eyjafjardardalur such deposits are especially abundant.

Near the mouth of Vatnsdalur, where the valley enters the wide lowland area south of Hunafjördur, a group of irregular, often conical, shaped hills occur, from 50 to 75 meters in height, and composed entirely of glacial material, each hill being of different composition and size of material. Altogether these deposits cover an area of possibly 2 square kilometers. Unfortunately, no time was available, in passing, to study them more closely and their mode of formation was not ascertained with

[4] Unfortunately rainy and foggy weather prevented the writer from securing satisfactory photographs of the glacier junction spurs of this region.

certainty. The fact that the sea once reached nearly, if not quite, to this locality, as indicated from old shorelines in the near vicinity, may account in part, at least, for the peculiar location of these deposits. They deserve detailed study.

Features of Ice-cap Erosion

ICE-CAP BEVELING

During the Glacial epoch, ice not only filled the valleys, but covered the entire plateau country and many mountain tops, leaving only isolated peaks here and there exposed. In Iceland its thickness over the upland area was from 500 to 800 meters less than in the river valleys, and consequently its pressure and power to abrade the uplands were greatly diminished, especially as the highland country lacked the gradient and directive influence of the river bed. In a water flood, the main work of erosion is accomplished in the river bed itself, and, likewise, in the glacial ice-cap the chief down-cutting action of the moving ice is confined to and concentrated in the submerged river valleys; but a glacial ice cap or flood is more permanent than a water flood, and preserves its level over a long period of time. Its surface acts, therefore, like a water surface (lake or ocean), as a plane of reference toward which exposed masses tend to be reduced. Above the ice-sheet all cliffs and peaks break down rapidly as a result of rapid temperature changes and consequent freezing and expansion of included moisture, and in a comparatively short time become reduced to the surface of the ice-sheet. An ice-sheet compares favorably with a body of water, in that its action is most intense along the coast and margins of the exposed land-masses. Its surface, moreover, is determined by the same general law of gravitation, but instead of being horizontal, as a water surface, it is, because of its greater viscosity or plasticity, gently inclined, and slopes away from the upland areas toward the sea or other lower level.

From the foregoing it is evident that upland rock-masses not far beneath the ice surface suffer little abrasion, while the exposed masses above the ice tend to be reduced rapidly to its level, with the result that if such ice action were continued long enough the mountain peaks in the area would be reduced to about the same general elevation and conform roughly in altitude to that of the ice-sheet as datum plane. The changes which would take place under such action are illustrated diagrammatically in figures 1 and 2. On recession of the ice, the upland surface, which before may have been exceedingly irregular, would resemble an old uplifted baselevel of erosion, sloping gently toward the sea or other baselevel and deeply dissected by glaciated river valleys. A cutting river tends to accentuate differences of elevation, while a water surface, as the ocean, tends to reduce all land surfaces to its level; in like manner, a valley glacier tends to cut deeper and to increase differences of altitude, while the ice-sheet tends to truncate the upland masses

FIGURE 1.—*Diagrammatic Section through a mountainous Area at the beginning of the ice-flood Period*

Ice is indicated by the dotted lines

FIGURE 2.—*Diagrammatic Section through the same Area*

Showing physiographic effects of subglacial action on the adjacent mountain mass, the level of the ice having been held for a long period at that indicated by dotted line.

to its general level. Such an aggregate of mountain tops may have reached baselevel so far as the ice-sheet is concerned, but it would not have been baseleveled in the ordinary sense of the word, although it might resemble very closely an old uplifted, warped and dissected baselevel of erosion.

THE UPLAND SURFACE IN ICELAND

Ice-sheet beveling of this type has been a factor, I believe, in the development of the old surface now marked on the uplands of northern Iceland, especially of the area east of Akureyri. There the backs of the mountains are gently arched, and present the appearance of an undulating, mature topography, approaching that of a peneplain, in which deep canyon-like cuts have been made by the valleys, and above which occasional sharp peaks project. But signs of glaciation are everywhere visible, glacial rounding and glacial erratics and debris occur, and indicate, at least, that the effect of the ice-cap should be regarded as a possible factor in the modeling of this upland surface.

The basalt formation, underlying this surface, dips gently to the north and northeast, and must have been influential in determining the upper limit of the ice-sheet. It is difficult, therefore, to decide just how much the present surface owes to inheritance and how much to ice-sheet beveling.

THE UPLANDS OF THE COAST RANGE, ALASKA

This particular difficulty is not encountered in southeastern Alaska, where glaciation was unusually severe during the ice deluge, and where a similar surface sweeps over the uplands of the Coast Range. There the backbone of the range is not flat lying basalt, but granite, in huge batholiths, extending from Alaska into British Columbia and covering an area 1,000 miles long and 100 miles wide. Its mountain tops show a decided tendency toward uniformity in elevation, and are, moreover, usually broad and only slightly arched; if the intervening precipitous valleys and canyons were filled to their apparently original profiles, an undulating, warped surface, sloping seawards from the center of the range, would result. This has been interpreted as proof of an original peneplain, uplifted and deeply incised, and general opinion among observers seems to be that the evidence warrants this conclusion.[5] The attempt to correlate this peneplain with others in the interior of Alaska has, however, met with serious difficulties, and the problem can not yet be regarded as completely solved. These difficulties are due in part to lack of detailed knowledge of the regions involved, but, until they are removed, the present peneplain hypotheses can not be considered entirely satisfactory.

That there is an accordance of summit levels among the mountains of certain parts of the Coast Range is a matter of observation; it is, also, a fact of observation that the surface passing over the tops of the upland areas is gently warped and rises from the coast toward the center of the range, the average gradient being about 1:150. Here and there above this surface sharp pinnacles and mountain spires project, which, on the peneplain hypothesis, would be considered monadnocks rising above the baselevel.

Another interpretation has been advanced to account for these relations, namely, that the original peneplain passed just above the serrated, non-glaciated peaks, in which case the undulating surface below has resulted from ice sculpture and postulates great ice erosion. This surface,

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[5] A. C. Spencer: Bulletin of the Geological Society of America, vol. 14, 1902, pp. 117-132.

A. H. Brooks: Professional Paper no. 45, U. S. Geological Survey.

G. K. Gilbert: Harriman Alaska Expedition, vol. iii, 1904, pp. 122-139.

however, which stretches over, and is supported solely by, the present pinnacles is a much warped surface, so irregular in fact as to render its interpretation as an original peneplain a mere guess rather than a working hypothesis which can be properly tested by observed facts.

It seems possible, however, that, in Alaska as in Iceland, ice-sheet beveling may have been an important factor in the observed planation of the present upland surface. This idea first occurred to the writer in 1904 while engaged in field work in southeastern Alaska, and although it is still only a working hypothesis it emphasizes a factor which seems not to have been regarded sufficiently heretofore.

At the time of the ice-flood the land area in the Coast Range of Alaska was covered with ice which reached all but the highest peaks. The upper limit of this ice-cap averaged about 2,000 meters elevation and is still plainly marked on the mountains. Below that limit the mountain slopes are rounded and abound in large, smooth curves, while above it sharp peaks and serrate ridges are the rule. That the ice-sheet remained for a long period of time at about the same elevation is evident from the distinctness with which its upper limit is chiseled in the peaks themselves. As in Greenland at the present time, the surface of the ice-sheet sloped gradually from the center of the range toward the sea. Such an ice surface is comparatively smooth and may well have served as the datum plane toward which the upland areas tended to be reduced.

CYCLE OF ICE EROSION

Undoubtedly, if this kind of erosion were sufficiently permanent in character, it would be possible to speak of a complete cycle of ice erosion. The deepening of the glacial valleys can not and does not continue indefinitely, as is evident from the present fiords and valleys, which are often over-deepened, where ice erosion was greatest, with consequent reversal of valley gradient for short distances and the formation of large hollows or basins in the valley floor. If the ice-cap were to remain long enough, the projecting mountain peaks would be practically obliterated, while at the same time some erosion would be effected along the top of the baseleveled portion as well as at the valley sides and heads, since the outward flow of the ice would still be kept up. A general lowering of the whole surface would thus result and the tendency toward baselevel of ice erosion would be still further accentuated, as with the lowering of the uplands a spreading out of the ice-cap might be expected. This last step of the process would require an exceedingly long time, much longer than that postulated by the Glacial epoch. The chief point of interest is the first step by which a roughly undulating upland surface may be produced resembling an uplifted and modified peneplain. Other factors, as isostatic adjustment, with simultaneous, differential degradation of the rising blocks, erosion above and below timber limit, highland glaciation, accordance of levels of upper surfaces of intrusive batholiths, with subsequent removal of overlying less resistant intruded rocks, etcetera, which have also been considered possible agents that might assist in bringing about the frequently observed tendency toward accordance in summit levels of mountainous areas, have been disregarded altogether in the above discussion in order to simplify the presentation. Such factors are obviously important, and must be and have been regarded in a consideration of the whole subject,[6] which, however, would lead too far in the present paper.

THE FIELD PROBLEM

The practical field problem, to determine precisely the part ice-sheet beveling has played in the formation of the present upland surface, is difficult, but the fact that this surface coincides with the upper limit of glaciation and follows this limit roughly down to the coastal margin of the ice-sheet is in itself a strong argument in favor of fairly intense ice-cap beveling. In mountainous regions, where these conditions might prevail, the slopes and gradient are usually such that all loose deposits, as original soil, which might serve to indicate peneplanation, or even morainic materials, are rapidly carried off and obliterated. Planation by glacial action should be most rapid in areas of soft, friable rocks, while remnants of an original peneplain should disappear most rapidly in such an area.

Many factors enter into erosion problems of this nature, and criteria have not been developed which might be used to determine definitely the influence and importance of the factor of ice-cap beveling. The attempt, only, has been made to show that under special conditions such ice-cap planation is possible to a certain extent, and, if so, to indicate that it was probably a factor in the development of the present baseleveled character of the upland areas in certain parts of Iceland and Alaska. It does not preclude the existence of a former peneplain, now warped, dis-

[6] In a paper, "Accordance of summit levels among Alpine mountains: the fact and its significance," Journal of Geology, vol. xiii, 1905, pp. 105-125, Mr. R. A. Daly has considered these factors in detail and with special reference to their bearing on the present problem.

sected, and uplifted, but it might serve to account for certain features of land sculpture which on the peneplain theory have been found difficult to explain satisfactorily.

Summary

The purpose of the foregoing pages has been primarily to direct attention to Iceland as an unusually favorable region for the study of the effects of mountain glaciation, both of the valley glacier and continental ice-sheet type. The fairly homogeneous and unaltered basalt formation of north Iceland offered practically uniform resistance to glacial action, and the forms developed therein by ice erosion are, therefore, simple and characteristic. The difference between the action of ice currents in a valley and the effect of the continental ice-sheet on the upland areas during the ice-flood period is plainly visible in Iceland.

An ice current in a valley is homologous to a river in its behavior; but in accord with the highly viscous or plastic state of ice, it acts as a blunt tool of wide bearing surface, and tends to clear out all of the smaller details of the river valley and to straighten and simplify its general shape and aspect.

The features produced by valley ice currents at the time of maximum extension fall naturally into two groups: (1) Those produced by the action of the valley ice current alone and undisturbed by tributary ice-streams, as U-trough shape of cross-section, straightening of river valley course, alignment of its sides, glacial grooves and markings along valley sides and bottom, steep valley head, often with cirque termination, etcetera; (2) those occurring at the junctions with tributary valleys, and resulting from the combined action of the trunk ice current and the disturbing tributary ice current. These features differ in character, dependent on the size of the tributary and its angle of confluence. (*a*) A small tributary ice-stream entering the main valley at any angle has but slight effect on the trunk ice current; its valley is undercut and left hanging, the elevation of its mouth above the main valley floor depending somewhat on its size. (*b*) In the case of a large valley uniting with the main valley at a wide angle and able practically to hold its own with the trunk glacier, tremendous forces are brought to bear on the valley bottom and sides, deep basin-like cuts far below baselevel are scoured out, while the valley sides are cut back and rise abruptly as steep cliffs, often overhanging and showing the characteristic double cliff slopes. At the confluence of several large converging valleys, the trunk valley is widened, its floor deeply eroded below baselevel, and its sides cut back until sheer cliffs

result. The junction spurs rise almost perpendicularly from their bases to high rounded domes, often beehive-shaped, and impressive because of their massiveness and simplicity. (*c*) At the confluence of a large valley at an acute angle with the main valley, the junction spur, between the two valleys, coincides closely with the direction of the ice currents. Its sides are truncated and aligned, but its crest line is worn down by the overriding, merging ice currents to a low, gently sloping tongue of bedrock pointing downstream. This type of spur is a characteristic feature of many glacial valleys, and for it the name of *glacier junction spur* is proposed. At and below these acute angled junctions, deep basins are also usually cut by the confluent ice-streams. At all such large junctions congestion of the ice may occur, and the uniform erosive action of the trunk ice-stream may be disturbed, with resultant irregularities in the valley rock floor. Later, on recession of the ice, irregularly shaped gravel deposits may be formed at such points.

These physiographic features which are characteristic of the action of an ice current indicate clearly that it erodes most rapidly along the valley floor and the lower half of the valley walls; there the thickness and momentum of the ice are at a maximum. Higher up the sides of the valley and nearer the original surface of the ice, the amount of direct erosive work accomplished by the ice current decreases rapidly, and as a result glacial valleys are usually steepwalled.

In contrast to an ice current, an ice-cap is homologous in its action to that of a large water surface, as the ocean, toward which exposed highland masses tend rapidly to be beveled. The ice-sheet spreads over wide areas; its surface is fairly uniform and slopes gently from the center of the country oceanwards and away from the elevated land masses which support it. As a whole, the ice-sheet lacks the directive influence of the valley which controls the ice current and renders possible the concentration of the tremendous forces of erosion which are dominant during the flood period of the glacial ice. As a consequence, the physiographic features developed by the ice-sheet are noticeably different from those resulting from ice-current action, even though such currents may be in part simply submerged portions of the ice-sheet itself passing through former river valleys. Immediately below the surface of the ice-sheet but little erosion is accomplished, as the ice there lacks sufficient thickness to be effective. Its attack, like that of a body of water, is directed chiefly toward the margins of exposed land masses. These elevated areas are, furthermore, subjected to the forces of highland erosion in its most virulent form, and soon break down and disappear beneath the ice cover.

The net result of the ice-sheet action, if continued long enough, would be, therefore, a truncation of the mountains at a common level, strongly resembling in appearance an uplifted marked and dissected peneplain. Ice-sheet beveling is suggested as a possible factor in the development of the observed upland surfaces, both in north Iceland and in the Coast Range of southeastern Alaska.

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TABLES FOR THE DETERMINATION OF CRYSTAL CLASSES[1]

(Read before the Cordilleran Section of the Society March 25, 1910)

BY W. S. TANGIER SMITH

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INTRODUCTION

One of the difficulties met by beginners in crystallography is the determination of the class to which a given crystal belongs. With a view to lessening this difficulty, the writer about two years ago prepared separate keys for the determination of the different classes belonging to each crystal system, and later a more comprehensive single key, including all the crystal classes. As this key has proved very satisfactory in use in the writer's classes, it is presented here in the hope that it may be of service to others. Various forms of the key have been worked out from time to time in the effort to find the simplest and most satisfactory arrangement, the two tables given here being those which have seemed the best in practice.

The first of these tables makes use of a center of symmetry as a basis for its main divisions, adopting the simpler of the two current definitions of that term; that is, the only condition assumed as necessary is the occurrence, for every plane on the crystal, of a corresponding, like, parallel plane on the opposite side of the center.

The other table has been so arranged as to require no reference to a center of symmetry; and at the same time the forms have been grouped in accordance with the recently proposed classification of Swartz.[2]

[1] Manuscript received by the Secretary of the Society June 27, 1910.

[2] Charles K. Swartz: Proposed classification of crystals based on the recognition of seven fundamental types of symmetry. Bull. Geol. Soc. Am., vol. 20, 1908, pp. 369-391.

The class names adopted in both tables are those used in the textbooks of Dana and Krause. In several instances where Dana gives no name to the group, one suggested by analogy from other related groups has been given parenthetically.

It should be noted that the terms 6-fold, 4-fold, etcetera, as used throughout these tables, refer to the number of times a crystal form can be brought into like positions merely by rotation about an axis without involving reflection in a plane at the same time (alternating axis). Considering the symmetry of the completed form, the class containing the rhombohedron of the third order (Trirhombohedral Group of Dana) would have a singular 3-fold axis of symmetry, since it may be brought into three like positions by simple rotation through 360 degrees about its singular axis. Considering the development of a complete form from a single plane, however, it has a 6-fold alternating axis, since each plane in the upper or lower half of a form characteristic of the class may be obtained from an adjacent plane in the opposite half of the crystal by a rotation of 60 degrees, followed by reflection in a plane perpendicular to the axis of rotation. For determinative purposes the simpler of these two aspects has been taken, not only in this class, but in all cases where an alternating axis is concerned. Whether the Rhombohedral and Trirhombohedral Groups of Dana belong to the Hexagonal System or to the Trigonal is another question and one which appears to the writer to depend on the fundamental definition of these two systems or subsystems. Without discussing the question (which is aside from the scope of this paper), the writer will merely state that on this point he has followed Dana and has placed both classes in the Trigonal division of the Hexagonal System.

Table No. 1

A. With Center of Symmetry

1. *With one or more planes of symmetry:*
   - (*a*) With but one axis of symmetry having a period greater than one-fold and with a single plane of symmetry, which is perpendicular to this axis.
     - Axis 6-fold—Hexagonal Bipyramidal Class or Pyramidal Group, Hexagonal System.
     - Axis 4-fold—Tetragonal Bipyramidal Class or Pyramidal Group, Tetragonal System.
     - Axis 2-fold—Monoclinic Prismatic Class or Normal Group, Monoclinic System.
   - (*b*) With more than one axis having a period greater than one-fold and more than one plane of symmetry.
     - ‡ With one or more singular axes and planes of symmetry perpendicular to them.

With a singular 6-fold axis—Dihexagonal Bipyramidal Class or Normal Group, Hexagonal System.

With a singular 4-fold axis—Ditetragonal Bipyramidal Class or Normal Group, Tetragonal System.

With three singular 2-fold axes perpendicular to each other—Orthorhombic Bipyramidal Class or Normal Group, Orthorhombic System.

‡‡ With a singular 3-fold axis and no plane of symmetry perpendicular to it—Ditrigonal Scalenohedral Class or Rhombohedral Group, Hexagonal (Trigonal) System.

‡‡‡ With no singular axes, but with three like axes perpendicular to each other.

Perpendicular axes 4-fold—Hexoctahedral Class or Normal Group, Isometric System.

Perpendicular axes 2-fold—Dyakisdodecahedral Class or Pyritohedral Group, Isometric System.

2. *With no planes of symmetry:*

(*a*) With a singular 3-fold axis of symmetry—Trigonal Rhombohedral Class or Trirhombohedral Group, Hexagonal (Trigonal) System.

(*b*) With no axis of symmetry other than one-fold—Triclinic Pinacoidal Class or Normal Group, Triclinic System.

B. WITHOUT CENTER OF SYMMETRY

1. *With one or more planes of symmetry:*

(*a*) With no or but one axis having a period greater than one-fold.

‡ Opposite ends of crystals unlike (axis polar).

Polar axis 6-fold—Dihexagonal Pyramidal Class or Hemimorphic Group, Hexagonal System.

Polar axis 4-fold—Ditetragonal Pyramidal Class or Hemimorphic Group, Tetragonal System.

Polar axis 3-fold—Ditrigonal Pyramidal Class or Rhombohedral Hemimorphic Group, Hexagonal (Trigonal) System.

Polar axis 2-fold—Orthorhombic Pyramidal Class or Hemimorphic Group, Orthorhombic System.

Polar axis 1-fold—Monoclinic Domatic Class or Clinohedral Group, Monoclinic System.

‡‡ Opposite ends of crystals like (axis not polar)—Trigonal Bipyramidal Class or (Trigonal Pyramidal) Group, Hexagonal (Trigonal) System.

(*b*) With more than one axis having a period greater than one-fold and more than one plane of symmetry (some of the axes may join the mid-points of opposite edges).

With a singular 3-fold axis and a plane of symmetry perpendicular to it—Ditrigonal Bipyramidal Class or Trigonotype Group, Hexagonal (Trigonal) System.

With a singular 2-fold axis and no plane of symmetry perpendicular to it—Tetragonal Scalenohedral Class or Sphenoidal Group, Tetragonal System.

With no singular axes, but with three 4-fold axes perpendicular to each other—Hextetrahedral Class or Tetrahedral Group, Isometric System.

2. *With no planes of symmetry:*

(*a*) With no or but one axis of symmetry having a period greater than one-fold.

Opposite ends of crystals unlike (axis polar).

Polar axis 6-fold—Hexagonal Pyramidal Class or Pyramidal-Hemimorphic Group, Hexagonal System.

Polar axis 4-fold—Tetragonal Pyramidal Class or Pyramidal-Hemimorphic Group, Tetragonal System.

Polar axis 3-fold—Trigonal Pyramidal Class or (Trigonal Pyramidal-Hemimorphic Group, Hexagonal (Trigonal) System.

Polar axis 2-fold—Monoclinic Sphenoidal Class or Hemimorphic Group, Monoclinic System.

Polar axis 1-fold—Triclinic Asymmetric Class or Asymmetric Group, Triclinic System.

Opposite ends of crystals like (axis not polar).

Axis 2-fold—Tetragonal Bisphenoidal Class or Tetartohedral Group, Tetragonal System.

(*b*) With more than one axis having a period greater than one-fold (some of them may join the mid-points of opposite edges).

With one or more singular axes.

With a singular 6-fold axis—Hexagonal Trapezohedral Class or Trapezohedral Group, Hexagonal System.

With a singular 4-fold axis—Tetragonal Trapezohedral Class or Trapezohedral Group, Tetragonal System.

With a singular 3-fold axis—Trigonal Trapezohedral Class or Trapezohedral Group, Hexagonal (Trigonal) System.

With three singular 2-fold axes perpendicular to each other—Orthorhombic Bisphenoidal Class or Sphenoidal Group, Orthorhombic System.

With no singular axes, but with three like axes perpendicular to each other; also with four like 3-fold axes—Sometimes one set, sometimes the other, the more prominent.

The like perpendicular axes 4-fold—Pentagonal Icositetrahedral Class or Plagihedral Group, Isometric System.

The like perpendicular axes 2-fold—Tetrahedral Pentagonal Dodecahedral Class or Tetartohedral Group, Isometric System.

Table No. 2

A. WITH NO PLANES OF SYMMETRY

1. *With no or but one axis of symmetry having a period greater than one-fold:*

(*a*) Opposite ends of crystals unlike (axis polar)—*Axial Order.*

Polar axis 6-fold—Hexagonal Pyramidal Class or Pyramidal-Hemimorphic Group, Hexagonal System.

Polar axis 4-fold—Tetragonal Pyramidal Class or Pyramidal-Hemimorphic Group, Tetragonal System.

Polar axis 3-fold—Trigonal Pyramidal Class or (Trigonal Pyramidal-Hemimorphic) Group, Hexagonal (Trigonal) System.

Polar axis 2-fold—Monoclinic Sphenoidal Class or Hemimorphic Group, Monoclinic System.

Polar axis 1-fold—Triclinic Asymmetric Class or Asymmetric Group, Triclinic System.

(*b*) Opposite ends of crystals like (axis not polar). (Symmetry by rotation about a singular axis, then by reflection in a plane perpendicular to the axis of rotation)—*Amebaxial Order.*

With a singular 3-fold axis—Trigonal Rhombohedral Class or Trirhombohedral Group, Hexagonal (Trigonal) System.

With a singular 2-fold axis—Tetragonal Bisphenoidal Class or Tetartohedral Group, Tetragonal System.

With only 1-fold axes—Triclinic Pinacoidal Class or Normal Group, Triclinic System.

2. *With more than one axis having a period greater than one-fold:*

(With one vertical axis and two or more lateral axes perpendicular to it. The lateral axes may join the mid-points of opposite edges)—*Polyaxial Order.*

(*a*) With one or more singular axes.

With one singular 6-fold axis—Hexagonal Trapezohedral Class or Trapezohedral Group, Hexagonal System.

With one singular 4-fold axis—Tetragonal Trapezohedral Class or Trapezohedral Group, Tetragonal System.

With one singular 3-fold axis—Trigonal Trapezohedral Class or Trapezohedral Group, Hexagonal (Trigonal) System.

With three singular 2-fold axes perpendicular to each other—Orthorhombic Bisphenoidal Class or Sphenoidal Group, Orthorhombic System.

(*b*) With no singular axis, but with three like axes perpendicular to each other; also with four like 3-fold axes—Sometimes one set, sometimes the other is more prominent.

The like perpendicular axes 4-fold—Pentagonal Icositetrahedral Class or Plagihedral Group, Isometric System.

The like perpendicular axes 2-fold—Tetrahedral Pentagonal Dodecahedral Class or Tetartohedral Group, Isometric System.

B. WITH ONE OR MORE PLANES OF SYMMETRY

1. *With no or but one axis of symmetry having a period greater than one-fold:*

(*a*) Opposite ends of crystals unlike (axis polar) and the plane or planes of symmetry passing through the polar axis—*Hedral Order.*

Polar axis 6-fold—Dihexagonal Pyramidal Class or Hemimorphic Group, Hexagonal System.

Polar axis 4-fold—Ditetragonal Pyramidal Class or Hemimorphic Group, Tetragonal System.

Polar axis 3-fold—Ditrigonal Pyramidal Class or Rhombohedral Hemimorphic Group, Hexagonal (Trigonal) System.

Polar axis 2-fold—Orthorhombic Pyramidal Class or Hemimorphic Group, Orthorhombic System.

Polar axis 1-fold—Monoclinic Domatic Class or Clinohedral Group, Monoclinic System.

(*b*) Opposite ends of crystals like (axis not polar), and with a single plane of symmetry which is perpendicular to the axis of symmetry—*Orthoaxial Order.*

Axis 6-fold—Hexagonal Bipyramidal Class or Pyramidal Group, Hexagonal System.

Axis 4-fold—Tetragonal Bipyramidal Class or Pyramidal Group, Tetragonal System.

Axis 3-fold—Trigonal Bipyramidal Class or (Trigonal Pyramidal) Group, Hexagonal (Trigonal) System.

Axis 2-fold—Monoclinic Prismatic Class or Normal Group, Monoclinic System.

2. *With more than one axis having a period greater than one-fold:*

(With one vertical axis and two or more lateral axes perpendicular to it, and with two or more vertical planes of symmetry intersecting in the vertical axis. The lateral axes may join the mid-points of opposite edges.)

(*a*) With a horizontal plane of symmetry (the lateral axes formed by the intersection of horizontal and vertical planes)—*Orthohedral Order.*

‡ With one or more singular axes.

With one singular 6-fold axis—Dihexagonal Bipyramidal Class or Normal Group, Hexagonal System.

With one singular 4-fold axis—Ditetragonal Bipyramidal Class or Normal Group, Tetragonal System.

With one singular 3-fold axis—Ditrigonal Bipyramidal Class or Trigonotype Group, Hexagonal (Trigonal) System.

With three singular 2-fold axes perpendicular to each other—Orthorhombic Bipyramidal Class or Normal Group, Orthorhombic System.

‡‡ With no singular axis, but with three like axes perpendicular to each other.

The like perpendicular axes 4-fold—Hexoctahedral Class or Normal Group, Isometric System.

The like perpendicular axes 2-fold—Dyakisdodecahedral Class or Pyritohedral Group, Isometric System.

(*b*) With no horizontal plane of symmetry (the vertical planes alternating with the lateral axes)—*Amebahedral Order.*

‡ With a singular axis of symmetry.

The singular axis 3-fold—Ditrigonal Scalenohedral Class or Rhombohedral Group, Hexagonal (Trigonal) System.

The singular axis 2-fold—Tetragonal Scalenohedral Class or Sphenoidal Group, Tetragonal System.

‡‡ With no singular axis, but with three like 2-fold axes perpendicular to each other; also with four like 3-fold axes. Sometimes one set, sometimes the other is more prominent—Hextetrahedral Class or Tetrahedral Group, Isometric System.

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ADDITIONAL NOTE ON THE GEOMETRY OF FAULTS[1]

BY HARRY FIELDING REID

(*Presented for publication to the Society March 3, 1910*)

In a recent paper simple projective methods were given for determining the displacement of a stratum at a fault.[2] It was pointed out that any displacement of a stratum could be represented by a linear displacement and a simple rotation. The rotation was determined by rotating the stratum first around a horizontal axis until it was horizontal, and then around a vertical axis until a line on it was properly oriented; these two rotations were then combined by the ordinary method of combining small rotations, namely, by representing the rotations by lines drawn in the directions of their axes, and with lengths proportional to the amounts of the rotations. The resultant axis is in the direction of the diagonal of the completed parallelogram, and its amount is proportional to the length of this diagonal. The positive direction of the axis is that in which the rotation appears right-handed.

This method, although correct for very small rotations and leading to no important error in most practical cases, is not accurately applicable except to very small rotations. It is desirable to give an accurate method which can be used in all cases. We must, therefore, find a simple method for determining the axis and the amount of a single rotation which will be equivalent to a rotation around a horizontal axis, followed by one around a vertical axis, however great these rotations may be.

In figure 1 let OA and OS represent the directions of the axes respectively, the rotation around these axes being right-handed when looked at from O. The simplest way to represent and combine the rotations is to consider a sphere of unit radius around O and determine the positions on it of certain points of the stratum before and after rotation. We suppose that the stratum passes through the horizontal axis OA and intersects the sphere in the great circle ADB. Let PDS be a great circle

[1] Manuscript received by the Secretary of the Society March 3, 1910. Not read at a meeting. Published by vote of Publication Committee.
[2] Geometry of faults. This Bulletin, vol. 20, 1909, pp. 171-196.

at right angles to OA; the angle through which the stratum must be rotated to make it horizontal is φ_1; the point D on the stratum is moved to D' by the rotation, and points on the axis OA are not displaced. Now rotate the stratum around the vertical axis OS through an angle φ_2; D' moves to D'', and A to A''. It is well known that any displacement of a sphere about its center can be represented as a rotation around a single axis, and that this axis is fixed if we know the displacements of two points on the surface of the sphere (such as D and A in this ex-

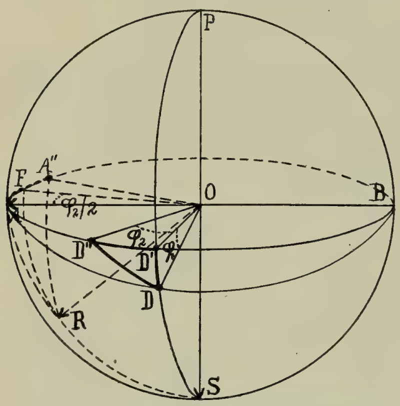

FIGURE 1.—*Combination of Finite Rotations*

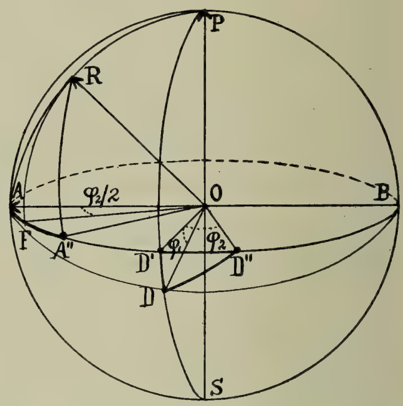

FIGURE 2.—*Combination of Finite Rotations*

ample). The point, R, where this axis pierces the surface of the sphere must be equidistant from A and A'', and from D and D''. To be equidistant from A and A'', R must lie on a great circle passing midway between A and A''; that is, its azimuth must make an angle $\varphi_2/2$ with OA. We must now find the point on this great circle which is equidistant from D and D''. It is simpler to do this by analytic than by projective methods. We take the ordinary expressions for the distance of R from D and D'' measured on the sphere, equate them, and find

$$\tan \delta = \sin \varphi_2/2 \cot \varphi_1/2,$$

which gives us the dip, δ, of the axis of rotation OR. We have seen that its azimuth makes an angle $\varphi_2/2$ with OA; its position is therefore completely defined.

To determine the amount of the rotation, φ, around OR, we solve the right-angled spherical triangle RFA and find

$$\tan \varphi/2 = \frac{\tan \varphi_2/2}{\sin \delta}$$

The angles δ and φ can be found very quickly with a table of logarithms.

Let us take the example of the former paper, namely, $\varphi_1 = 15°$; $\varphi_2 = 10.3°$; then $\varphi_1/2 = 7.5° = 7° 30'$; $\varphi_2/2 = 5.15° = 5° 09'$.

log sin $\varphi_2/2$	8.9531	*log tan* $\varphi_2/2$	8.9549
log cot $\varphi_1/2$	0.8806	*log sin* δ	9.7508
log tan δ	9.8337	*log tan* $\varphi/2$	9.2041
	$\delta = 34° 17'$		$\varphi/2 = 9° 5'$
			$\varphi = 18° 10'$.

By the simpler, but less accurate, method we find *tan* $\delta = \varphi_2/\varphi_1 = 5.15/7.5 = 0.6866$; hence $\delta = 34° 28'$; and $\varphi = \sqrt{\varphi_1^2 + \varphi_2^2} = 18.16°$, or $18° 10'$; the value of φ is the same and that of δ very nearly the same as those obtained by the accurate method, but the azimuth of the axis, which was taken in the plane of the horizontal and vertical axes, was wrong by $\varphi_2/2$, or about 5 degrees.

Rotations in opposite directions introduce no complications. We can always take a position so that the horizontal axis shall point to the left; that is, that the forward part of the stratum shall be rotated upward. Then the vertical axis of rotation may either point downward, as in figure 1, or upward, as in figure 2; these two include all possible cases. We use the same formulæ for either case, always regarding φ_1 and φ_2 as positive, the one difference in the results being that the axis *OR* will lie behind or in front of *OA*, according as the vertical axis points downward (figure 1) or upward (figure 2). The angle between *OF* and *OA* will be $\varphi_2/2$ in both cases.

The following table shows values of δ and φ when calculated by the accurate and by the approximate method (the latter indicated by the primes). The values selected for φ_1 and φ_2, with the exception of the last, make them together equal to 90°; if their sums were smaller, the errors would be less :

φ_1	φ_2	φ	φ'	Dif.	δ	δ'	Dif.
80°	10°	80° 30′	80° 37′	07′	5° 56′	7° 08′	1° 12′
65	25	69 10	69 38	28	18 45	21 02	2 17
50	40	63 14	64 02	48	36 16	38 40	2 24
45	45	61 38	63 37	1° 59	42 44	45 00	2 16
10	80	80 30	80 37	07	82 15	82 52	37
80	80	108 08	113 07	4 59	37 27	45 00	7 33

On examining this table it will be seen that the error made by following the approximate method will be small for any rotations likely to occur. In general, results sufficiently accurate will be obtained by determining the dip of the resultant axis and the amount of the resultant rotation around it by the approximate method; but the azimuth of the resultant axis will make an angle $\varphi_2/2$ with the direction of the horizontal component axis. The positive direction of the resultant axis will dip downward if the positive direction of the vertical component axis is downward and *vice versa*.

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SUPPLEMENTARY NOTE ON THE ORGANIZATION OF THE GEOLOGICAL SOCIETY OF AMERICA[1]

BY C. H. HITCHCOCK

(*Read before the Cordilleran Section of the Society March 26, 1910*)

The first volume of the Bulletin of the Geological Society of America opens with a historical sketch prepared by Alexander Winchell at the request of the Council. Reference was made first to the Association of American Geologists organized in 1840, and to its inclusion of the Naturalists, and to its development into the American Association for the Advancement of Science in 1847. With the multiplication of sections at the last reorganization Geology and Geography were combined with Section E. Many of the members were dissatisfied with this arrangement. These dissentients and others assembled at Cincinnati in 1881 and formulated their views in the following "circular letter," which was mailed to all the known geologists in the country:

"*To the Geologists of America:*

"At a meeting of the geologists in attendance at the Cincinnati session (1881) of the American Association for the Advancement of Science, the undersigned were appointed a committee to correspond with American geologists respecting the formation of an *American Geological Society*, the result of such correspondence to be reported at the next meeting of the American Association for the Advancement of Science.

"Pursuant to such instructions, it is deemed best to present sundry considerations, some of them brought forward at Cincinnati, which seem to render it desirable that such a society be organized in America, and which have been approved, and hereby are presented jointly by the committee.

"The committee are desirous of eliciting opinions from all active and professional geologists, to the end that more judicious and effective action may be taken at the next meeting.

"1. The science of geology, with its kindred branches of palæontology and lithology, has made rapid progress in America—perhaps more rapid than in any other country—in the last twenty years.

[1] In the absence of the author, this paper, which supplements the original historical sketch prepared by Alexander Winchell and printed in volume 1 of the Bulletin of the Society, was read by Secretary G. D. Louderback.

Manuscript received by the Secretary of the Society May 9, 1910.

"2. The literature of geology is largely distributed through numerous scientific journals and in the proceedings of miscellaneous scientific societies, to procure which is difficult and expensive.

"3. The present facilities afforded through the American Association for the Advancement of Science are insufficient, and are unavailable by the working geologists of the country—because: (*a*) The meetings are held in the summer, which is the geologist's working season. In order to be present he must interrupt his work and leave the field, often at considerable expense, especially if he has a party with him. (*b*) Its brief meetings partake largely of the nature of vacation pleasure parties, and much of the time is engrossed by reception, gratulation, and excursions. (*c*) There is no sufficient avenue of publication of the work of geologists, and especially of palæontologists. (*d*) The association has become large, widespread, and popular in its work, membership, and organization that its spirit necessarily and properly is not favorable to the development of any special work through its own agency.

"4. The geologists, as a body, have no way of expressing their views on important state, national, or international measures, except through the medium of the American Association, at the meetings of which there is a perceptible and increasing lack of attendance and interest on the part of geologists, in consequence of which the actual views of the geologists of the country on such questions can not be obtained and expressed correctly.

"5. There is a need of co-ordination of the results of State surveys, to the establishment of greater uniformity in nomenclature and classification.

"6. There is a need of co-operation on the part of palæontologists and of some system in describing and publishing new species.

"7. There is no strictly geological magazine or journal in America.

"8. There is no strictly geological society in America.

"9. There are numerous such societies and journals in Europe, as well as journals and societies devoted exclusively to the branches of palæontology and mineralogy.

"The committee desire also to disclaim any intention to trespass on the field and plans of the American Association for the Advancement of Science, or to criticise it in any way as to the discharge of its functions. Its tendency is to popularize science and to advance its acceptance by the world by diffusing scientific knowledge and by announcing important discoveries, and as such its sphere of activity is one that no special scientific body can occupy, but which still will be aided by the existence of tributary organizations, such as that contemplated by this circular.

"Persons to whom this circular is addressed are requested to communicate promptly their views and recommendations to any member of the committee, in order that a report may be presented at the Montreal meeting of the American Association embodying such recommendations as may be warranted by the correspondence and summarizing the same.

"(Signed) N. H. Winchell, State Geologist of Minnesota, Minneapolis, Minnesota.

John R. Procter, State Geologist of Kentucky, Frankfort, Kentucky.

Henry S. Williams, Professor of Palæontology, Cornell University, Ithaca, New York.

John Collett, State Geologist of Indiana, Indianapolis, Indiana.

G. C. SWALLOW, Professor of Geology, etc., University of Missouri, Columbia, Missouri.

WM. J. DAVIS, Palæontologist, Assistant Geological Survey of Kentucky, Louisville, Kentucky.

S. A. MILLER, Palæontologist, Cincinnati, Ohio."

In response to this call, the geologists convened at Montreal and discussed the subject further, as explained in the official report of their meeting, as follows:

"At the Montreal meeting of the American Association for the Advancement of Science in August, 1882, a number of American geologists convened to consider the question of organizing an American Geological Society. Alexander Winchell was chosen Chairman and C. H. Hitchcock Secretary. Several meetings were held during the week, whose proceedings may be summed up in the following statements:

"N. H. Winchell, chairman of the committee appointed at Cincinnati, in 1881, to correspond with geologists upon the expediency of forming such a society, reported that from the circulars he had sent out ninety answers had been received, all but two of which expressed themselves as favoring the project. H. S. Williams reported that he had received answers from thirty persons, and S. A. Miller reported that he had received answers from six persons. In both cases the answers were favorable, so that out of one hundred twenty-six expressions of opinion, one hundred twenty-four were in favor of the project and only two opposed.

"A committee, consisting of Jed Hotchkiss, R. P. Whitfield, and C. H. Hitchcock, was appointed to consider the situation and to make recommendations. They reported that it was expedient to establish a geological magazine. This report was accepted and adopted.

"The Cincinnati committee reported a constitution for the establishment of a geological association, which was discussed and laid upon the table, and the committee was requested to continue its investigations and report the next year at the Minneapolis meeting.

"A committee consisting of C. H. Hitchcock, J. S. Newberry, N. H. Winchell, H. S. Williams, and G. H. Cook, was designated to confer with Major J. W. Powell, of Washington, in order to ascertain what encouragement might be afforded by him in the support of a geological magazine.

"On motion of James Hall, it was voted to recommend to Section E the appointment of a committee to confer with the Director of the United States Geological Survey in regard to cooperation between the National and State Geological Surveys.

"The following named persons were present at these meetings: A. Winchell, N. H. Winchell, E. T. Cox, H. S. Williams, W. H. Niles, E. Orton, E. T. Nelson, Jed Hotchkiss, R. P. Whitfield, A. H. Worthen, I. C. White, E. W. Claypole, G. H. Cook, J. W. Spencer, J. S. Newberry, James Hall, T. S. Hunt, H. F. Walling, E. D. Cope, and C. H. Hitchcock.

"The committee named above to confer with Major Powell reported that he expressed a desire for the success of the proposed magazine and a readiness to contribute to its welfare. He did not, however, think it would be well for him to be identified with its inception."

The following is a copy of the report of what occurred at the Minneapolis meeting:

"At the Minneapolis meeting of the American Association for the Advancement of Science an adjourned session of the geologists interested in the establishment of a geological society and a geological magazine was held, August 21, 1883. A letter addressed to the President of Section E from the Mineralogical and Geological Section of the Philadelphia Academy of Sciences was read, in which the formation of an American society of geologists was favored, 'provided that such action shall be generally concurred in by American geologists, and that its permanency and a liberal publication of professional papers be insured by an ample endowment fund.' The letter was written by the Secretary, Charles A. Ashburner.

"After various discussions, it was voted that a committee be appointed to confer with the Mineralogical and Geological Section of the Philadelphia Academy of Natural Sciences with reference to the formation of an American geological society and the establishment of a geological magazine.

"The President and Secretary of Section E of the Philadelphia meeting of the American Association for the Advancement of Science were named as *ex officio* members of this committee, the others to be designated by the President, N. H. Winchell. As finally constituted, the committee consisted of N. H. Winchell, E. A. Smith, C. A. White, C. H. Hitchcock, and John Collett.

"The geologists present at the Minneapolis meeting were N. H. Winchell, J. S. Newberry, T. S. Hunt, E. Orton, J. W. Spencer, E. T. Cox, J. W. Powell, W. Upham, J. P. Lesley, E. W. Claypole, and C. H. Hitchcock.

"A true report:

"C. H. Hitchcock,
Secretary.

"Minneapolis, Minnesota, *August* 22, 1883."

For various reasons, no meetings of this committee were held at Philadelphia in 1884, nor at the subsequent sessions of Section E at Ann Arbor in 1885, at Buffalo in 1886, and at New York in 1887.

Those who were interested in the establishment of a geological magazine organized, and began with the year 1888 the publication of the American Geologist, a monthly periodical, with seven editors and proprietors, and the editorial office and management were located at Minneapolis. This was a private enterprise approved of but not supported by the committee.

It was now 1888. The officers appointed by the geologists in 1882-1883 had apparently become discouraged at the outlook. Perceiving that unless another effort was made very soon the project must fail, the writer proposed to N. H. Winchell that they jointly issue a call for another meeting of geologists to determine whether they might be ready to organize. They felt called upon to assume this initiative because they represented those who had been officially connected with the movement originating at Cincinnati.

The following is the text of the call, drawn up by the secretary and published in the American Geologist for June, 1888. Extra copies were distributed far and wide, and many geologists signified their approval of the scheme.

"Geologists will recall the fact of the appointment of a committee of their number at the meeting of the A. A. A. S. in 1881 to consider the advisability of forming an *American Geological Society.* This committee sent out circulars asking for opinions, and received 126 answers to their inquiries, all but two of which expressed a belief in the expediency of organizing such a society. These facts were reported at Montreal in 1882. It was there voted expedient to establish a geological magazine. A proposed constitution for a society was presented, discussed, and laid upon the table for future consideration. At the adjourned meeting in 1883, at Minneapolis, the questions of the magazine and society were further considered. Little was accomplished beyond the appointment of a committee to confer with the Mineralogical and Geological section of the *Philadelphia Academy of Natural Sciences.* For various reasons no meeting was called to discuss the subject at Philadelphia. Since then regret has been expressed by some who were at first opposed to the project that the effort had not been pressed. At the New York meeting of the International Congress Committee (A. A. A. S.), August, 1887, the following resolution was passed: 'That the American Committee of the International Congress will approve of a call for the meeting of an American Geological Congress, whose object shall be the discussion of important geological questions.'

"The chief objection to the establishment of an American Geological Society has been the fear that its existence would impair interest and attendance at the meetings of the American Association for the Advancement of Science. But if the new society could be made identical with Section E, retaining the officers chosen at the meetings of the A. A. A. S., and having the power to assemble at other times during the year, adopting necessary regulations for the extra sessions, it would seem as if the geologists might obtain all the advantages of a special organization.

"The chairman and secretary of the above named committee of American geologists would therefore call upon all American geologists to assemble with them at Cleveland, Ohio, at 3 p. m. of Tuesday, August 14th, the day before the next session of the A. A. A. S., and, if deemed expedient, organize a society subject to the following limitations:

"1. The members of the society shall be also members of the A. A. A. S.

"2. The president and secretary of the new society shall be the gentlemen elected to these offices by the A. A. A. S.

"3. It will be recommended to Section E at its formal session to offer an amendment to the constitution of the A. A. A. S., that Section E may be allowed to hold meetings at such time and place as they may desire, independently of the other sections, subject to their own regulations.

"(Signed) N. H. Winchell, *Chairman.*
"C. H. Hitchcock, *Secretary.*"

This final call proved to be a success. At the day appointed a large number of geologists assembled at Cleveland and unanimously resolved that it was time to organize an American geological society. The precise relations of the new organization to Section E advocated in the call were modified. It was agreed that the original members of the new society should be restricted to those who were enrolled in the American Association for the Advancement of Science, but that after January 1, 1889, other persons would be eligible. The new society was to be entirely distinct from Section E, while the summer meetings were to be held at the same locality.

Thirty-seven persons subscribed to the provisional constitution before the adjournment of the Association at Cleveland, and by November 1 more than one hundred names had been obtained, and the establishment of a vigorous geological society was assured. No further mention of the various steps by which the organization was perfected need be mentioned, as they are given in volume 1, our object being simply to complete the records of the early history of the organization.

A second historical sketch, giving the details subsequent to the Cleveland meeting and the final organization at Ithaca December 27, is given in the American Geologist for February, 1889.

The names of the thirty-seven persons who were the first to accept the conditions of fellowship at Cleveland are the following:

J. S. Newberry.	Peter Neff.
Alexander Winchell.	J. W. Powell.
George H. Cook.	Julius Pohlman.
H. S. Williams.	J. F. Kemp.
N. H. Winchell.	J. H. Chapin.
L. E. Hicks.	A. W. Vogdes.
Edward Orton.	Geo. F. Kunz.
C. H. Hitchcock.	C. W. Hall.
J. C. Branner.	Frederick W. Simonds.
John R. Procter.	S. G. Williams.
J. J. Stevenson.	G. F. Wright.
W J McGee.	J. E. Todd.
Chas. C. Abbott.	Homer T. Fuller.
D. S. Kellicott.	H. B. Patton.
Albert L. Arey.	W. E. Taylor.
A. D. Morrill.	N. H. Crump.
J. W. Spencer.	W. H. Pettee.
H. P. Cushing.	A. E. Foote.

Persifor Frazer.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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RICHMOND AND GREAT BARRINGTON BOWLDER TRAINS[1]

BY F. B. TAYLOR

(*Presented extemporaneously before the Society December 28, 1910*)

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PREVIOUS INVESTIGATORS

The Richmond bowlder train has been a subject of study and discussion among geologists since before the middle of the last century. It was discovered and first traced across the country by Dr. S. Reid, formerly of Richmond, Massachusetts, and, according to Benton, was first described by him in 1842. Reid had several papers on this subject, and it was discussed by Edward Hitchcock and by H. D. and W. B. Rogers in 1845, by E. Desor in 1848, and by Sir Charles Lyell in 1855. These early writings were at a time when the glacial theory of Louis Agassiz was new and not yet generally accepted. The different ways in which these authors explain the origin of the bowlder trains is interesting now chiefly from a historical point of view.

LOCATION AND CHARACTERISTICS OF RICHMOND TRAIN

The Richmond train extends from Fryes Hill, otherwise known as "The Knob," which stands on the line between the towns of New Lebanon and New Canaan, in the northeastern part of Columbia County, New York. A small area on the top of the knob is composed of chloritic or amphibolite schist. The exposure of this rock is about half a mile long and a quarter of a mile wide and forms the lightest knob of the Canaan and Lebanon range.

[1] Manuscript received by the Secretary of the Society October 3, 1910.
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The principal train, concerning which so much has been written, extends in a nearly straight line from Fryes Hill about south 40 degrees east. It is easily traced for 7 or 8 miles into Berkshire County, Massa-

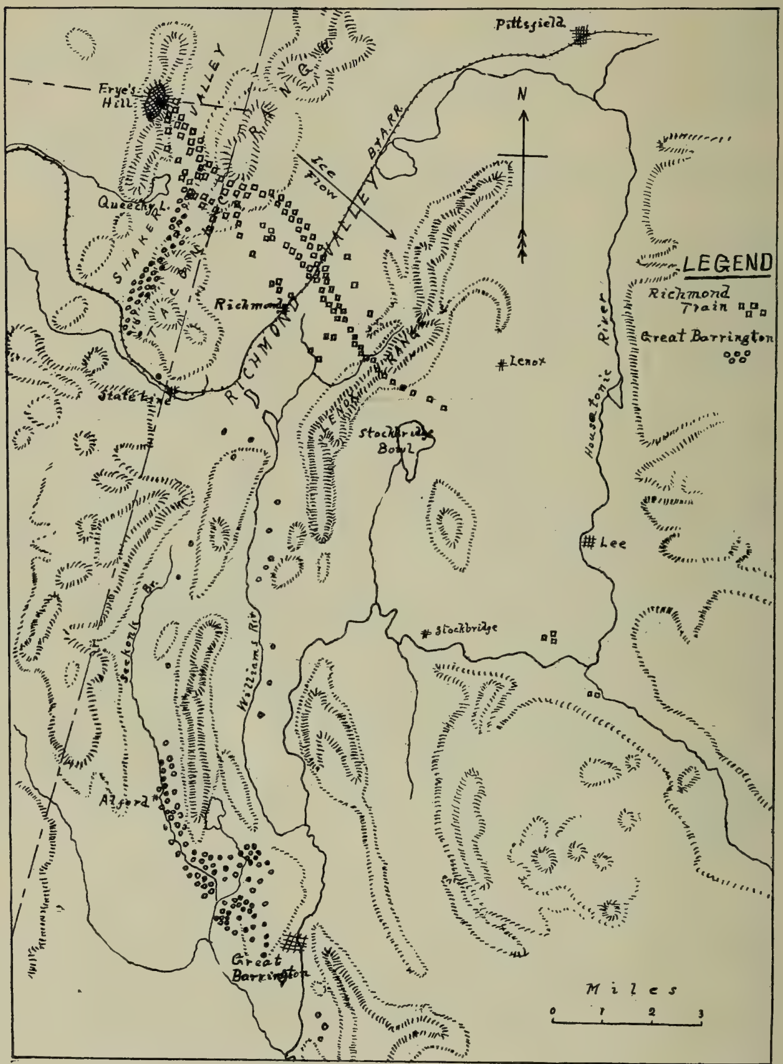

FIGURE 1.—*Map showing Richmond Train and Distribution of Great Barrington Bowlders*

chusetts, and is faintly traceable for about twice this distance. The bowlders are quite numerous and many of them are large in the first 7 miles, but beyond this they grow scattered and of smaller size.

The most remarkable characteristic of this train is the nearly straight course which it takes diagonally across a region of mountain ridges and valleys. From Fryes Hill the train crosses Shaker Valley, then over the summit of the Taconic Mountain range, then over the wider Richmond Valley, then over the Lenox Mountain range, thinning out in the neighborhood of the Stockbridge Bowl and in the Housatonic Valley beyond. The accompanying sketch map shows the course of the Richmond train, and also the distribution of the Great Barrington bowlders so far as now mapped.

Benton, who has written the most detailed description of the Richmond trains,[2] recognizes several separate lines. On his map he shows two lines near Fryes Hill and four in Richmond.

The less prominent lines are composed mainly of metamorphic limestone and sandstone from other parts of Canaan and Lebanon range than that in which the amphibolite is situated, but they are weak and poorly defined, and the chief interest centers in the principal train, composed of amphibolite blocks.

The writer's study of the bowlders of this region was incidental to other work and was not so thorough as could be wished. But it was found that, besides the bowlder trains previously described, there is apparently another which takes a different direction from Fryes Hill, and that the bowlders composing it, although of the same rock as the Richmond train, are very different in their appearance and condition. The whole line of the newly found train has not yet been studied in detail, so that the results presented are somewhat incomplete and the conclusions in some degree tentative.

As stated above, the Richmond train runs in a direction about south 40 degrees east from Fryes Hill. All the bowlders of this train are sharply angular in their forms and fresh in their appearance. They seem to show no weathering nor any rounding off of corners and edges, but have the appearance of freshly quarried blocks. Many of them are of large size, especially some of those in Shaker Valley and on the flanks of Perry Peak. The one most often described is the great bowlder in a pasture lot west of the road 2 miles north of Richmond station. This stands about 8 feet high, 14 feet long, and 10 feet wide, and a conside able part is under ground.

Location and Characteristics of the Great Barrington Train

The train recently found appears to begin in Shaker Valley southeast of Fryes Hill on the slope east of Queechy Lake, and from this place

[2] E. R. Benton: "The Richmond bowlder trains." Bulletin Museum of Comparative Zoology, Cambridge, Massachusetts, 1878, accompanied by a large detailed map.

runs southward along the western flank of the Tatonic Range to the base of Cunningham Hill, 2 miles northwest of State Line station on the Boston and Albany Railroad. In all probability it continues south and southeast through the gap at State Line, and thence southward toward Alford and Great Barrington, for in the valley of Seekonk Brook, in the vicinity of Alford, which is 5 miles northwest of Great Barrington, bowlders of this same amphibolite schist occur in considerable numbers, and their number increases southeastward toward Great Barrington, where they seem to have been concentrated by the ice movement. This interval of about 8 miles between the two parts of the train as now reported has not been examined in detail. From the few observations made, it is not believed that the bowlders are so numerous in it nor the train so well defined. For some distance north of Alford comparatively few were found in the valley, but the hills were not examined.

The form and condition of these bowlders, both in that part of the train near Fryes Hill and near Great Barrington, is strongly contrasted with those of the Richmond train. Every bowlder found in this southward train is well rounded and shows marked effects of weathering. Not only is the surface discolored by oxidation to a grayish green in place of the clear, dark green of the fresh, angular surfaces of the Richmond blocks, but some of the effects of weathering have penetrated beneath the surface a quarter to half an inch, and deeper in diminishing strength. Among these bowlders none of great size were found, the largest being about 4 feet in diameter, but a great many were found with diameters of 1½ to 2 feet. In certain places in the valley of the Seekonk below Alford and among the drumlins back of Great Barrington, as many as thirty or forty of these bowlders were found built into 200 feet of ordinary stone wall along the roadside, and there still remains a sprinkling of them in the fields. There are also in the same walls rounded and weathered bowlders of several other varieties of rock. Among these is one which must be carefully distinguished from the amphibolite on account of its close resemblance in color and hardness. This is the green Rensselaer grit. It is many times more common, but is readily distinguished by characteristics of a freshly fractured surface. So far as observed, the bowlders along the base of the hill south of Queechy Lake are mostly smaller and not so many as near Great Barrington, but they are of the same rounded, weathered character, entirely unlike the angular blocks of the Richmond train.

The bowlders near Great Barrington are 16 to 17 miles from Fryes Hill and nearly straight south of it. On account of this distance and direction, there is, perhaps, some reason to doubt whether they were derived from that hill. But on this point it may be said that the bowlders south of Queechy Lake, being of the same character, suggest the beginning of a train leading southward, and occasional bowlders of the same kind occur between State Line and Great Barrington, both in the valley of Seekonk Brook and of Williams River, farther east, although particular search for them has not been made in this interval.

It is, of course, possible that the Great Barrington bowlders were derived from some other nearer source than Fryes Hill, but no other outcrop of amphibolite schist is known in the region north and northwest of Great Barrington. Smaller bowlders of the same rock in the same condition were found occasionally on a line running south-southeast from Great Barrington nearly to the south line of Massachusetts. Several were found where this line crosses Konkapot Valley 2 or 3 miles south of Mill River. Two or three small bowlders of this same rock were found about 3 miles south of Tolland, Massachusetts. The latter seem likely to belong to the Richmond train, for they lie in line of its trend produced.

Amphibolite schist occurs also on Haystack Mountain north of Norfolk, Connecticut, and at points from 1 to 2 miles farther north, but none of the bowlders mentioned, neither those in the Konkapot Valley, north of Haystack Mountain, nor those south of Tolland, can be supposed to come from these outcrops by glacial transportation, for the trend of the ice movement was toward this mountain from Konkapot Valley, and they would have to be carried 10 miles a little north of east to reach the locality south of Tolland.

Probable History of Bowlders of the Great Barrington Train

The rounded, weathered condition of all the bowlders of the Great Barrington train bespeaks a very different history from that of the Richmond train. The Richmond blocks appear to have been plucked from the summit of Fryes Hill by the last ice-sheet, carried on or in the upper part of the ice and strewn across the country on the line of ice movement. They appear to have been deposited or let down on the surface. The Great Barrington bowlders, on the other hand, are water worn and weathered and more intimately associated with the till, as if they had been transported in the dirt-laden basal part of the ice.

These bowlders were in all probability detached from Fryes Hill in preglacial or interglacial times and were water worn and weathered before the coming of the Wisconsin ice-sheet. These characteristics must have been acquired by them before they were finally incorporated into the drift and deposited where they are now found.

There are also some amphibolite bowlders in this condition in the line of the Richmond train, for Benton says: "In a cut on the Boston and Albany Railroad, three-quarters of a mile northeast of Richmond station, are completely rounded and polished bowlders, some of which have a length of 4 or 5 feet. They are composed of limestone and of chlorite schist, and a few exhibit well marked parallel striæ." [3] That there was a pre-Wisconsin ice invasion of this region is not open to doubt, for a deep, indurated bed of bowldery till, plainly older than the Wisconsin, is well exposed in the excavation for the new water power plant on the Housatonic River just below Glendale. The Great Barrington bowlders, however, may not constitute a train of the same character as the Richmond train. It seems probable that their immediate source was a great weathered talus around Fryes Hill, and perhaps also from bowlder paved river beds near it. It seems difficult to account otherwise for the rounded, weathered condition of these bowlders.

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[3] Loc. cit., p. 25.

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ABSTRACTS OF PAPERS PRESENTED AT THE TWENTY-SECOND ANNUAL MEETING OF THE SOCIETY BUT NOT PUBLISHED IN FULL IN THE PRECEDING PAGES OF THIS VOLUME, TOGETHER WITH DISCUSSIONS OF PAPERS AS FAR AS PRESERVED

E. O. Hovey, *Secretary*

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POST-TERTIARY HISTORY OF THE LAKES OF ASIA MINOR AND SYRIA

BY ELLSWORTH HUNTINGTON

(*Abstract*)

A study of the lakes of the Anatolian plateau and of Syria was one of the chief objects of the Yale Expedition of 1909. The lakes fall naturally into five groups, namely, normal fresh-water lakes with ordinary outlets, salt lakes of the common type without outlets, karst lakes with underground outlets in limestone regions, glacial lakes with no definite outlets, but kept fresh by underground seepage, and crater lakes with similar indefinite outlets. In Syria the number of lakes is small; there are no glacial lakes, and the other four types are sharply differentiated. The most interesting problems are, first, the part played by lava flows and deltaic deposits in the formation of lakes Huleh and Galilee, and, second, the problematic former outlet of the Dead Sea and the fluctuations to which this lake has been subject in post-Tertiary times. In Anatolia the number of lakes is large and the various types merge into one another. For instance, crater lakes are sometimes saline, normal lakes have in some cases been drained by underground outlets, and salt lakes have in the past overflowed and been fresh. A comparison of the ancient strands and deposits of the lakes of both regions affords abundant data for the reconstruction of the varied climatic history of western Asia since the close of the Tertiary era.

Discussion

Dr. F. P. Gulliver: I should like to ask Doctor Huntington if he found any marked differences in the forms of his series of five shorelines, such that it might be possible to distinguish each earlier from later formed shorelines. Such distinctions of form would be helpful in determining the time since the elevation of the land took place. With these five shorelines in Palestine and Asia Minor so closely connected with historic data, it seems as if it would be possible to make out a succession of forms resulting from weathering, stream action, wind action, etcetera, since the several shorelines were formed.

Prof. W. M. Davis: Is it necessary to suppose that the two lakes had ever risen high enough to overflow the inclosing highlands, and thus begin the erosion of their outlet gorges? Is it not probable that the gorge cutting may have accompanied the uplift of the highlands; or, in case the lake basins occupy weak structures, that the erosion of the basins has been accomplished in the same period of time as the erosion of the gorges? Hercegovina shows similar features without any indication of overflowing lakes.

Prof. D. W. Johnson: I wish to report the occurrence, in eastern West Virginia, of a small valley from which the stream has been recently diverted to an underground course through limestone caverns, the stream reentering the valley farther down its course. Thus we have a continuous stream-carved valley, one section of which is no longer occupied by a stream. If this condition prevails for some time, the upper part of the valley might be reduced slightly below the level of the deserted portion. Obstruction of the opening into the caverns through which the stream disappears would produce a lake which might overflow at times through the deserted section of the valley. Possibly a similar condition may explain the lakes and deserted outlet gorges mentioned by Doctor Huntington.

Prof. Joseph Barrell: Small rhythmic fluctuations of climate, of which the longest well established cycle is 35 years, have become generally accepted, but are regarded by most meteorologists as of small magnitude and not leading toward larger and more permanent climatic changes. Doctor Huntington, in his work, however, has brought together a mass of data and develops conclusions of very different import. Climatic changes of pronounced character and enduring for centuries are seen to have taken place within historic times—changes of such magnitude that they are recognizable from their geologic records. The question arises as to how these climatic changes are related to the geologic past. Are they parts of a cycle some thousands of years in length which has consequently not yet become completed within historic times, and is such a cycle, if it exists, one which in rising and falling series has run through geologic times?

As Lyell showed that the present is the key to the past in the crustal history of the earth, similarly the key to the climatic history is to be found in the study of the present climates and their fluctuations. It is seen from Huntington's work that the recent changes are not dependent on the precession cycle of about 21,000 years, and this may go far toward clearing up several difficulties. F. B. Taylor,[1] for instance, in his study of the moraines of recession south of the Great Lakes finds fifteen of the first order between Cincinnati and Mackinac.

At the time, in 1896, it seemed necessary to correlate these changes with the precession cycle, but this gives an excessive duration for the retreat of the ice-sheet, and Taylor remarks that a period of between 5,000 and 10,000 years would seem to accord more closely with the phenomena.

Further, in 1893, Gilbert[2] called attention to a rhythmic alternation of argillaceous and calcareous beds in a portion of the upper Cretaceous of Colorado running through 3,900 feet of strata, a single rhythm averaging 4 feet. He considers the alternations to be of climatic origin and, because no other competent

[1] Moraines of recession and their significance in glacial theory. Journal of Geology, vol. v, 1897, pp. 421-465.

[2] Sedimentary measurement of Cretaceous time. Journal of Geology, vol. iii, pp. 121-127.

climatic cycle was known to him, he assumed that each rhythm represented the precession cycle. But this gives, as he himself has pointed out, what is generally regarded as the excessive estimate of 20,000,000 years for a part of upper Cretaceous time. Similar sedimentary rhythms, though generally less regularly developed, have been noted in many formations, extending even into the Algonkian.

It is seen that the precession cycle does not appear to fit well to either the late Pleistocene moraines of recession or to the Cretaceous shales. Huntington's work, by permitting us to consider climatic cycles of intermediate periods and independent of precession, brings these observations into greater harmony with other lines of investigation.

It must not be forgotten, however, that recent work in radioactivity tends to give far greater estimates to the duration of geologic time, and that it would be premature to abandon the precession cycle as one of the still possible explanations of these geologic rhythms, but the field of geologic theory is enriched by the additional possibility that these recurrent changes are similar in nature to those changes which have operated with pronounced effect in historic times.

Dr. Ellsworth Huntington: To Professor Davis's criticism on nomenclature I would reply that the point as to the term "fiords" seems well taken. The term "Alpine" is properly applicable to mountains like those of the Taurus, which rise to a height of 10,000 feet and which contained glaciers during the Glacial period. My use of the term applied not merely to rock forms, however, but also to the wooded aspect of the region. We need terms which describe not only form, but also the nature of the vegetation of a region.

Meaning of the gorges: There may possibly have been an uplift whereby the cutting of gorges was occasioned at the outlets of lakes Kara Viran and Koghadeh. I saw no evidence of this, however, in the form of other young or revived valleys such as would be occasioned by uplift. The material of the broad valleys where the lakes lie appears to have been largely carried off in solution through underground outlets.

As to age of strands: The strands of the Dead Sea and Lake Buldur vary greatly in age and in the amount of change which they have suffered. The characteristics of each are sufficiently pronounced, so that it ought to be possible to identify them merely from the amount of weathering and erosion. It is possible that sufficient study would enable us to estimate the age of the strands in years by comparing them with the minor features which can be definitely dated.

TIDE-WATER GLACIERS OF PRINCE WILLIAM SOUND AND KENAI PENINSULA, ALASKA[3]

BY U. S. GRANT

(Abstract)

The Alaskan coastline between the mouth of Copper River and Cook Inlet is deeply indented by bays and fiords, the heads of some of which are occupied by glaciers discharging into the sea. These have been mentioned in the reports on this district and some of them were studied by the Harriman Alaska Expe-

[3] Read by title, in the absence of the author.

dition in 1899. Work on the geology and ore deposits of this district for the United States Geological Survey has given opportunity for further study of these glaciers and the mapping of the fronts of all of them. As a rule there has been since the growth of the present forest a period of retreat in the case of these glaciers. One, the Barry, has its front 2 miles farther back than in 1899. The best known of these glaciers, the Columbia, was advancing rapidly in the summer of 1909 into the forested zone along its front.

OSCILLATIONS OF ALASKAN GLACIERS

BY R. S. TARR AND LAWRENCE MARTIN

(Abstract)

The National Geographic Society's Alaskan Expedition of 1909 observed the following glacial oscillations. In Yakutat Bay the Marvine lobe of Malaspina glacier and the Atrevida, Haenke, and Variegated glaciers have ceased the advance which began in the winter of 1905-1906. The Hidden glacier has advanced over 2 miles since 1906, but has now begun to shrink away from the new shore moraines. Hubbard glacier has advanced slightly. Lucia glacier is newly crevassed and advancing this summer (1909) and is riding up on a nunatak. These oscillations confirm the earthquake-avalanche theory for glacial advance, proposed in 1906 by the senior author, and furnish facts as to the brevity of such advances. On the lower Copper River the Childs glacier was more active in 1909 than 1908, but the position of the front remains unchanged. The Miles, Childs, and Baird glaciers are essentially as in 1884, 1885, 1891, and 1900. In eastern Prince William Sound the Valdez and Shoup glaciers are slowly receding. The Columbia glacier has advanced rapidly since 1908 and is building moraines and destroying the forest, as was observed by Prof. U. S. Grant early in 1909 and by the National Geographic Society expedition later in the season. The events in the glaciation of Prince William Sound differ decidedly from those in the Yakutat Bay region.

Discussion

Dr. F. E. Matthes: The cause assigned for the spasmodic advance of the Alaskan glaciers by Professors Tarr and Martin is no doubt a competent one and probably the true one; at the same time it is not a necessary one. The mode of advance of glaciers is normally spasmodic. Why this should be is not clear, as the mechanics of glacial flow involved is as yet imperfectly understood. The fact, however, has been satisfactorily established by experiments on ice-flow under regulated pressure recently made by German investigators and described by Professor Hess in his treatise "Die Gletscher." These experiments show that ice confined in a reservoir remains inert under steadily increasing pressure until a certain point is reached when flow sets in, slowly at first, but increasing rapidly in velocity, even though the pressure remains constant or is diminished. The flow then continues with gradually diminishing velocity until the reservoir is well depleted, when the ice-mass returns to its inert state. The conditions in nature very closely parallel those obtaining in the experiments. The annual overflow from a glacial cirque does not correspond to the annual accretions; but the snow keeps on accumulating for several years, as a rule, until sufficient pressure is reached to inaugurate a strong and rapidly accelerated forward movement. A conspicuous advance of the glacial front results, which does not stop until the cirque is drained to a low level.

Professor MARTIN replied that it seemed to him that the fact that normal glacial advance is spasmodic, as shown by Mr. Matthes, did not make any particular complication in the question discussed. The localization of the spasmodic advances in and near Yakutat Bay make it evident that these advances are due to earthquake-avalanching during the earthquakes of September, 1899, which were central in Yakutat Bay.

SOME EFFECTS OF GLACIER ACTION IN ICELAND

BY FRED E. WRIGHT

Published as pages 717-730 of this volume.

DISCUSSION

Prof. W. M. DAVIS remarked that "U-shaped" was an unsatisfactory term with which to characterize glacial troughs because many of them are round-bottom V's, the difference between the two forms probably corresponding to young and mature phases of glacial erosion.

CLIFF SCULPTURE OF THE YOSEMITE VALLEY

BY F. E. MATTHES [4]

(Abstract)

The Yosemite Valley may be epitomized as a glacial canyon laid in structurally aberrant materials. It is to the latter circumstance chiefly that the valley owes its remarkable wealth of sculptured forms. These are not inherently a product of either stream or ice erosion; they are a function of the structure of the country rock. The granites of the Yosemite region may be pictured as consisting of many huge monolithic masses imbedded in a matrix of more or less strongly fissured rock. This unusual structural habit naturally carries with it extreme inequality of resistance to disintegration. As a consequence rock structure has played a prominent rôle in the evolution of the topography of the region. The Yosemite landscape indeed reflects in its features the structural character of the materials from which it has been carved; its dominating heights consist invariably of intractable monoliths; its canyons and gulches are due to zones of easily eroded fissile rock. The glacial cross cliffs and lake basins in the valley floors, the headlands and embayments of the rock walls have in each case evolved in obedience to local structural controls. The very trend and profile of each cliff has been determined by structural planes. Indeed every rock form and monument of the valley is to be interpreted as an expression of its associated structures. This applies also to those notches and niches about the waterfalls, which have heretofore been explained as the result of the shifting of the falls in Glacial times.

[4] Introduced by M. R. Campbell.

DISCUSSION

Prof. D. W. JOHNSON: Field observation and the inspection of the excellent maps of the Yosemite Valley prepared by Mr. Matthes impress me with the important control exerted by joint planes on the details of cliff sculpture in the Yosemite, and also with the remarkable fidelity with which contours represent such details when the right man is behind the pencil. An examination of Mr. Matthes' map when it first appeared convinced me that Branner's explanation of the notches beside the Yosemite Falls would not apply in a number of the cases cited, and an examination of those notches last summer confirmed my belief that many of the notches result from weathering along joint planes and have never been occupied by streams. Only a few weeks ago did I learn that Mr. Matthes had come to the same conclusion a year or two earlier.

Mr. Matthes apparently supports the theory that stream erosion on the jointed rocks is competent to explain the peculiar features of the Yosemite, sometimes ascribed to glacial erosion; in other words, the joint structure explains the broad bottomed, overdeepened valley. I should like to suggest another interpretation, namely, that the glacial overdeepening of the main valley and the oversteepening of its walls has made possible the remarkable cliff sculpture guided by joint planes. Not until the glacier formed its deep trough, with almost vertical sides, could weathering and gravity work so effectively as to produce the present topography. Overdeepening by normal stream erosion even in jointed or fissured rocks does not seem competent to produce a deep, open, flat-floored valley, whose tributaries hang 2,000 and more feet above the valley floor.

FURTHER LIGHT ON THE GORGE OF THE HUDSON

BY JAMES F. KEMP

(Abstract)

The paper gave the latest evidence furnished by the deep borings in the Hudson Valley at the Storm King crossing of the New York City aqueduct, and cited the results of the construction of the Pennsylvania Railroad tunnels opposite Thirty-third street, New York. The facts were interpreted, involving a discussion of the general problem of glacial overdeepening.

DISCUSSION

Dr. J. W. SPENCER: I should like to ask if Professor Kemp has any evidence of this being the former northward development of the Hudson Channel north of Storm King, as topographic features suggest such diversion. Lake Champlain is 400 feet deep, besides which there has been considerable northward warping in recent post-Glacial time, and the depth of the Saguenay is about 900 feet. The Gulf of Saint Lawrence shows a recent subsidence of 2,000 feet or more. The topography suggests that the Highlands once formed a divide between a branch of the northern Saint Lawrence drainage and the more rapid grades to the drowned Hudson River canyon extending to more than 100 miles seaward from New York.

Professor KEMP replied that there were ledges of Hudson River slate all across the river a few miles above Troy, and that unless there were a buried channel, of which nothing was known, the river could not have found a passage north.

GLACIAL LAKES AND CHANNELS NEAR SYRACUSE[5]

BY T. C. HOPKINS

(*Abstract*)

Where the south-moving glacier met the north slope of the Allegheny plateau with its northward drainage there would be considerable ponding of the waters that could be released only by an east or west outlet. During this east-west drainage across the divides between the north-flowing streams numerous high channels would be formed. Where these glacial streams drop over a cliff, a basin or pool would be eroded that after the disappearance of the glacial stream would remain as a pond or lake. The writer has evidence to indicate that a number of these so-called glacial lakes were not formed in this way, but are due in large measure to solution by the ground waters.

ISOBASES OF THE ALGONQUIN AND IROQUOIS BEACHES AND THEIR SIGNIFICANCE

BY J. W. GOLDTHWAIT

Published as pages 227-248 of this volume.

Discussion

Dr. J. W. Spencer said that he was much interested in the work of Professor Goldthwait, who had extended the surveys of the Algonquin beach to the west about Lake Michigan. Doctor Spencer also stated that all his own leveling of the Algonquin some twenty years ago, as also that of the Iroquois beach on the north side of Lake Ontario, had been made by use of the "Y"-level. He also said that he had shown that the upward warping of the Huron and Ontario regions pointed to an ellipse north of the city of Ottawa rather than to a center of glaciation. This was some three years before De Geer visited the region. Doctor Spencer said that he was particularly gratified that the newer details brought out by Professor Goldthwait fully confirmed the original conclusions.

Mr. F. B. Taylor: The gravelly delta at Peterboro, Ontario, is apparently in a slightly constricted bay connecting with Lake Iroquois, as has been stated by Coleman, and may be very slightly higher than the Iroquois beach on that account. But it is also in the belt bordering on the Archean area, where the old water plane as found at Kirkfield and Orillia takes on a relatively sudden increase in the rate of its northeastward rise. Thus it may after all stand at or very nearly at the Iroquois level, although it seems at first too high.

Professor Goldthwait replied as follows: These methods have been presented in earlier papers. The crest of a beach ridge or the foot of a sharply cut bluff, where most typically developed, have been selected for measurement. Usually the modern lake has been used as a starting point from which to run the levels. The original variations in height of the beach and the possible error in the leveling together are probably not over 7 or 8 feet. In spite

[5] Read by title, in the absence of the author.

of this variation, however, which cannot be eliminated from the measurements, the twenty measurements on the Algonquin beach south of the hinge line have a variation of only 7 feet.

SHORELINES OF THE GLACIAL LAKES IN THE OBERLIN QUADRANGLE, OHIO

BY FRANK CARNEY

(*Abstract*)

The paper described the varying features shown in the shorelines of the Maumee, Whittlesey, and Warren Lake stages, and discussed the factors involved.

GLACIAL INVESTIGATIONS IN THE LAKE SUPERIOR REGION IN 1909[6]

BY FRANK LEVERETT

(*Abstract*)

The studies in 1909 were in the district west of Marquette, the district to the east having been covered in previous years. They were extended across northern Michigan and Wisconsin into Minnesota, and embraced the territory directly tributary to Lake Superior from the south and part of the drainage to Lake Michigan and to the Mississippi, but did not reach to the border of the Driftless Area. The moraines as well as shorelines of glacial lakes indicate a general northeastward recession of the ice-field. Interlobate moraines were formed on the Keweenaw Peninsula and the Bayfield Peninsula, and there was also a reentrant at the Porcupine Mountains, with slight lobation on either side. The western Superior glacial lake, Lake Duluth, was found to have extended eastward beyond the Keweenaw Peninsula before a lowering to the level of its successor, Lake Algonquin, took place. It reached an altitude more than 700 feet above Lake Superior on the eastern part of the Keweenaw Peninsula, while its altitude at the western end of the Superior basin was only about 465 feet above Lake Superior. Its isobases trend approximately west-northwest to east-southeast, thus harmonizing with those of Lake Nipissing, as worked out by Taylor, for the basins of the three upper Great Lakes. A differential uplift of nearly 3 feet per mile is found along a line running from Bruce crossing north-northeast to Calumet. There appears to have been very little uplift during the life of Lake Duluth, its highest shoreline being nearly parallel with the highest shore of Lake Algonquin. The uplift occurred mainly during the life of Lake Algonquin. The shore of Lake Nipissing is submerged westward from the Bayfield Peninsula, and is but 5 to 6 feet above Lake Superior in the vicinity of Bayfield. It reaches 40 feet above the lake on the Keweenaw Peninsula.

DIVERSION OF THE MONTREAL RIVER

BY ROBERT BELL

(*Abstract*)

This paper described a remarkable example of change in the destination of a large river, in which the stream has been diverted in post-Glacial times into

[6] Read by title, in the absence of the author.

a new channel that carries its waters all the way to its present mouth in a straight course of 90 miles, which lacks only 45 degrees of being exactly opposite to that of the upper part of the stream, as well as its former continuation below the point at which the change took place; that is to say, that at a certain point the course of the river was turned round through an angle of not less than 135 degrees, or from a north to a southeast direction, and made finally to discharge into the Atlantic Ocean instead of Hudson Bay. This singular occurrence was rendered possible from the fact that in one part of its course the river was barely able to pass across what has now become a low divide, and that a slow rising or tilting of the land to the southward gradually stopped the northward flow of the river, while at the same time the changing conditions induced a process of "stream-robbing" through a dam of loose drift material a short distance east of this increasing obstruction. The paper described numerous facts, which, taken together, seem to prove the manner in which this important and interesting phenomenon was accomplished.

RELATIONSHIP OF NIAGARA RIVER TO THE GLACIAL PERIOD

RELATIVE WORK OF THE TWO FALLS OF NIAGARA

INTERRUPTION IN THE FLOW OF THE FALLS OF NIAGARA IN FEBRUARY, 1909

BY J. W. SPENCER

Published as pages 433-448 of this volume.

Discussion

Prof. W. M. Davis asked for further information concerning the basis for correlating the deposits discovered by borings with the glacial and interglacial epochs.

Prof. Lawrence Martin asked whether the several beds interpreted as interglacial showed signs of weathering or not.

Mr. F. B. Taylor: I am not familiar with the particular facts which Doctor Spencer has just presented, but it is interesting to note that they appear to agree so far as they go with the exposures near Toronto. It is significant as bearing on the probable depth of the Saint Davids Channel that not only did the boring stop without reaching rock, but if the warm-climate beds found near Toronto occur here they must be at a still lower level, and so far as this is indicative it suggests that rock bottom may be considerably lower.

Doctor Spencer, in answer to Professor Martin's inquiry as to the state of differential decay or oxidation of the deposits in the borings, said that such observations were impossible in the partial admixture of materials brought up by the operations.

In reply to Professor Davis's question as to the interglacial deposits, he stated that his paper is a correlation of the pre-Niagaran deposits with the glacial and interglacial deposits on the northern side of Lake Ontario at Toronto rather than with those of the Mississippi Valley. The most important interglacial period is that represented by a soil with a more northern flora than at present (now buried 180 feet)—at a time of enormous denudation.

The fuller history of the Glacial period is better studied east of Toronto, where the strata are exposed in Scarboro Heights.

ORIGIN OF CLIFF LAKE, MONTANA

BY G. R. MANSFIELD[7]

(*Abstract*)

Cliff Lake lies in south central Montana about 5 miles northwest of the continental divide, where the latter makes the pronounced bend that partly encloses the basin of Lake Henry in eastern Idaho. The lake was brought to public notice in 1872 by Hayden, who described it as formed in a volcanic fissure. At the present time popular belief ascribes the lake to a similar origin. The paper discussed the evidence for the hypothesis of volcanic origin and presented alternative evidence to show that the lake, though set deeply in a lava plateau, really occupies a portion of a river valley that was interrupted in early maturity by the advent of a glacier which left a series of morainic dams and thereby produced a group of small lakes, of which Cliff Lake is perhaps the most notable.

Discussion

Prof. W. M. Davis suggested the possibility that landslides from the steep valley sides might explain the formation of the lakes, and noted the fact that the hummocky surfaces of landslides often simulate the form of moraines.

Professor Mansfield replied that the possible effect of landslides had been considered by him, but that the evidence appeared to favor a glacial origin for the obstructions which held in the lakes.

ROCK STREAMS OF VETA MOUNTAIN, COLORADO

BY H. B. PATTON

Published as pages 663-676 of this volume.

Discussion

Prof. D. W. Johnson expressed his appreciation of the very instructive lantern slides shown by Professor Patton, and recalled an example of rock-streams in the so-called crater of the San Francisco Volcano, in Arizona, which terminates in a high and steep crescentic slope, and which he at first interpreted as a terminal moraine.

Dr. F. E. Matthes: On the northeast side of Pikes Peak there occur several deep, cirque-like depressions containing what appear to be strong morainic ridges composed of rock debris. The glacial origin of the latter features seemed, at the time of observation, beyond doubt. They may, however, turn out to be rock-streams like those described by Professor Patton, and renewed examination of them seems therefore desirable.

Professor Patton said in reply that he had at times been inclined to attribute somewhat similar structures in high mountains to creep of the rock detritus, influenced by presence or absence of parallel snow-drifts, but that

[7] Introduced by U. S. Grant.

this can not apply to the Veta Mountain rock-streams. It is also plain that these rock-streams can in no way be due to glacial action, as no signs of glacial action are to be seen within 10 or more miles. It is quite possible, therefore, that rock-streams may occur in many other places, heretofore unsuspected.

MEANDERS AND SCALLOPS

BY MARK JEFFERSON

(*Abstract*)

Meanders, or balanced swings in river courses, occur from source to mouth, though most fully developed in the plains part. The embayments or scallops produced in their upper course by meanders that come in contact with the bluff are of identical measurement with the meanders and serve to estimate the ancient volume of the stream.

BEACH CUSPS

BY MARK JEFFERSON

(*Abstract*)

Beach cusps are points of gravel or sand that occur at times on almost all beaches where these materials exist. Perspective foreshortening gives them a fictitious appearance of regularity. They are caused probably in various ways, by waves that play squarely on shore, either under on-shore winds or in still weather after storms, when the diminishing waves accommodate themselves more and more to the shape of the bottom and the configuration of the shore.

NORTH AMERICAN NATURAL BRIDGES

BY HERDMAN F. CLELAND

Published as pages 313-338 of this volume.

Discussion

Dr. Horace C. Hovey remaked that he had no doubt that there were several different ways in which natural bridges might be formed, as had been so admirably explained by the speaker. For himself he had been most interested in those found in caverns, or left as the strongest parts of cavern roofs, whose weaker portions had fallen in. Of the latter, the Natural Bridge of Virginia had long been considered an illustrious example. This theory was first advanced in Jefferson's Notes on Virginia, who credits it to Doctor Gilman, by whom it was claimed that the valley, or canyon, through which Cedar Creek flows was once a cavern, of which this great arch was the sole remnant. Doctor Hovey had seen small underground bridges in parts of Mammoth Cave and in some Virginia caves, particularly what is styled "Al Serat," in Jewel Cavern, in the Green Briar Valley.

A noble specimen of natural bridge-making abroad was seen in the Bramabiau Cave, near where the Jurassic limestone seems to roll like a billow against the granite flanks of the Cevennes Mountains in France. The small river, Bonneheur, flows under an arch about 40 feet wide and 30 high, emerges again to daylight at the distance of about 500 feet, then plunges under another arch, flows some 4,000 feet, to emerge finally, with a depth of 16 feet, in a cataract 35 feet high under a stupendous arch, estimated to be 300 feet high. Although styled a cave, the Bramabiau is really a gigantic natural bridge.

SALT MARSH FORMATION NEAR BOSTON, AND ITS GEOLOGICAL SIGNIFICANCE

BY CHARLES A. DAVIS[8]

(Abstract)

A description of some of the salt marshes near Boston, including newly discovered facts regarding the way in which they are formed and their bearing on geological history. These marshes have not been formed in depressions behind barrier beaches as the result of filling by plants and sediments in the resulting ponds, but have a quite different origin, which is plainly indicated in their structure and in the character of the plant material contained in them. The marshes contain easily interpreted records of a continued post-Glacial coastal subsidence that is still going on at a steady and uniform rate that it is possible to determine. The interpretation of these deposits also has an important bearing on the theories of formation of coal.

GEOLOGICAL SUGGESTIONS DERIVED FROM A NEW ARRANGEMENT OF THE ELEMENTS

BY B. K. EMERSON

(Abstract)

The elements were arranged in the order of the periodic law on an increasing helix—that is, on a half octave, two octaves, and four double octaves—and interesting physical and geological relations were brought out.

MECHANICS OF FAULTS

BY HARRY FIELDING REID

(Abstract)

The forces which can be considered as active in producing faults are: horizontal tensions and compressions, vertical forces (upwards or downwards), and horizontal drags on the under surface of the crust. It was shown that in a uniform crust horizontal forces alone would produce normal or thrust faults having hades of 45 degrees; that the available vertical forces alone would produce normal faults with a smaller hade, and that the addition of a tension to a vertical force increases the hade, whereas the addition of a pressure diminishes it. Drags generate pressure and tensions; they may cause faults with horizontal displacements. The elevation of large regions is due to vertical and not to tangential forces.

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[8] Introduced by David White.

NEW LIGHT ON THE GEOLOGY OF THE WASATCH MOUNTAINS, UTAH

BY ELIOT BLACKWELDER

Published as pages 517-542 of this volume.

Discussion

Mr. S. F. Emmons said that he was much gratified in listening to Mr. Blackwelder's paper, for it explained many things that had puzzled him just 40 years ago last summer, when, as geologist of the Survey of the 40th Parallel, he surveyed the region under consideration, and a few years later was called on to outline its geological formations on the map. In those days "overthrust faulting" had not been invented. The range was regarded as a great anticlinal fold, with its axis somewhat warped by a north-south compression and its western flank cut off by the great Wahsatch fault. It had been his hope that this great range, which Dana in the last edition of his text book had characterized as the most comprehensive single range in the world, would long before this have been surveyed in detail, as Mr. Blackwelder's work showed that it well deserved. Time was so limited when the 40th Parallel work was done that by no means all of the country could be adequately studied, though it was all mapped. For instance, to Ogden Canyon, of which he speaks, only a single day's work could be given; consequently it was only possible to ride to the head and back. In the summer of 1869, not only the whole Wahsatch range and the western end of the Uinta Mountains, but also over 5,000 square miles of desert ranges to the west had to be surveyed, and necessarily the ground had to be traversed very rapidly.

As to the Weber quartzite, Mr. Emmons had observed that it thinned out to the southward as well as at the north, there being less than 2,000 feet in the Park City region, as Mr. Boutwell's detailed work has shown, while at Mount Timpanogos, still farther south, it seems to be represented by an alternating series of limestones and quartzites, called by him the Intercalated series. On the other hand, in the next range to the westward, the survey of the Brigham district shows over 8,000 feet of quartzites in the Weber series.

HAWAIIAN VOLCANOES

BY REGINALD A. DALY

(Abstract)

Evidence was given for the view that the vent at Kilauea is an opening in the roof of a large laccolith. This conception offers a tentative explanation of the observed independence of Halemaumau and Mokuaweoweo (Mauna Loa). A small, visible laccolith on Hawaii was described. The paper also included a discussion of (*a*) the method by which the heat is maintained in Halemaumau; (*b*) the differentiation of Mauna Kea alkaline rocks from basaltic magma, and (*c*) the development of Mauna Kea in its present form.

GENETIC CLASSIFICATION OF ACTIVE VOLCANOES

BY T. A. JAGGAR, JR.

(*Abstract*)

The writer has studied seven active volcanoes in the last 8 years. Mercalli's classification by types of eruption and kinds of lavas is not genetic and hence contains many overlaps. Volcanoes show kinship of origin and stages of growth related to a common origin. It is believed that a classification based on (1) the unity of all volcanic phenomena and (2) diversity of types, measured by viscosity of lavas, will produce a rational and significant series. This series was shown in tabular form.

TARUMAI, A CUMULO-VOLCANIC ERUPTION IN JAPAN, 1909

BY T. A. JAGGAR, JR.

(*Abstract*)

This volcano is in southeastern Yezo. It became active January 11, 1909, with a culminating eruption on April 12. Between April 12 and April 23 an extraordinary hard lava dome, a phenomenon hitherto unknown in Japan, rose within the crater. The volcano otherwise is a cinder cone. The size, shape, and mechanism of the dome resemble Pelé and Bogoslof. The writer visited the volcano in May, 1909, accompanied by Japanese geologists.

Discussion

Prof. W. M. Davis: If it be intended that the seven types, beginning with Kilauea and ending with Fuji, represent successive stages of development, is it possible to find field evidence to show that the present Vesuvius has had a previous Kilauea stage, and that the present Fuji has been preceded by the various stages from the Kaluea through the Tarumai and Pelé stages? In the very nature of the case the evidence for Fuji would seem too difficult to recover. I can not help fearing that, as more examples are brought into this scheme, it will be found that the sequence of development is much more irregular than is here suggested.

Mr. F. L. Ransome pointed out that whereas Professor Jaggar's classification of volcanoes is avowedly based on viscosity of the lavas erupted, this basis of grouping is apparent in the first five only of his eight types. The remaining three characterizations of primary rank in the classification, namely, no lava extruded, ancient lava only, and laccolithic lava, are not expressive or even suggestive of increasing degrees of viscosity, but involve classification on other bases than the one adopted in the first part of the table. Mr. Ransome questioned, moreover, the validity of including laccolithic intrusions in a classification of volcanoes, suggesting that the laccolithic form may be assumed by magmas of a wide range of viscosity and of varied chemical composition.

STRUCTURE OF THE NORTHERN PORTION OF THE EUREKA-VOLCANO-BURNING-SPRINGS ANTICLINE, IN PLEASANTS, WOOD, AND RITCHIE COUNTIES, WEST VIRGINIA

BY F. G. CLAPP

(*Abstract*)

A geological examination of the northern portion of this anticline, followed by the plotting of its structure on the government topographic maps, shows that the anticline is not even approximately straight or of uniform height or width, as had generally been assumed by geologists and oil operators; on the contrary, it is very irregular. The strike of this portion of the anticline ranges from north 20 degrees east to north 10 degrees west. The width of its flat crest ranges from an eighth to half a mile, while the maximum altitude of any given formation on the axis varies several hundred feet in different portions of the anticline, thus making a series of alternating domes and saddles. Since the oil development here is largely a matter of the past, the relations of the oil pools to the structure can be studied to good advantage. It was found that the productive portions of the anticline correspond closely with the domes, while between them the saddles were always barren of oil for distances, sometimes, of more than 2 miles along the axis. As a rule, the shallower oil sands were productive on an anticlinal crest, while the deeper ones were dry there, but productive farther and farther from the crest, according to relative depth. Since this paper was written, the statements made regarding complexity of the anticlinal structure here have been corroborated by the West Virginia Geological Survey in their mapping of the structure.

Discussion

Dr. I. C. White: The same results described in this interesting paper of Mr. Clapp's have also been found by Prof. G. P. Grimsley, one of my assistants, whose report on Wirt, Wood, and Ritchie counties is now passing through the press. Also, during the present summer, another of my assistants, Mr. Roy V. Hennen, has traced this same arch southwestward from Burning Springs, dying down, but curving westward and passing through the great Walton oil field. Prof. E. B. Andrews was the first geologist to describe the anticline in 1861, in a paper published in the American Journal of Science, and its study led him to the discovery of the anticlinal or structural theory of oil and gas accumulation.

GENERALIZED SECTION THROUGH THE APPALACHIAN MOUNTAINS OF MARYLAND

BY CHARLES K. SWARTZ

(*Abstract*)

A generalized section was given through the Appalachian Mountains on the Maryland-Pennsylvania state line, with a detailed section through the central Appalachians. It was shown that certain types of structure characterize the region discussed, being observed both in its major and its minor features. It was further shown that these characteristics are to be seen in the general

structure of the northern Appalachians. The question of the origin of canoe-shaped folds was discussed briefly. Finally, the relation of the drainage system to the structure was referred to.

Discussion

Dr. Arthur Keith: In the Appalachian folding I have seen south of the Potomac the character of the folding is directly due to the character of the strata involved. Thin-bedded rocks make small folds and crumplings, and massive rocks make large and smooth folds. According as the strata at the surface are heavy or thin-bedded, the character of the folding which we see varies. It varies also as the position of the massive beds changes in the section. The pressure is transmitted mainly by the massive beds. Where they occupy the lower part of the section the folds have a tendency to be upright, and where they are in the upper part of the section there is a strong disposition toward overturning. The changes and interactions of these factors make marked and general changes in the nature of the deformation from north to south along the Appalachians. Folding, which is distinctive of Maryland and Pennsylvania, with comparatively little overturn, passes into folding and faulting with much overturning in lower Virginia, and into faulting with subordinate folding in Tennessee, Georgia, and Alabama, the overturning at the same time becoming more pronounced.

SOME INSTANCES OF FLOWING WELLS ON ANTICLINES

BY F. G. CLAPP

(Abstract)

The paper described several unrecorded flowing artesian wells of a peculiar type. The flows are from unproductive oil wells in the northern Appalachian region. The first mentioned instance is on the Eureka-Volcano-Burning-Springs anticline in Pleasants County, West Virginia. This anticline consists of an alternating series of saddles and domes, and the flowing wells are situated on a saddle of the anticlinal crest midway between two domes. The source of the water is one of the Carboniferous sandstones, which does not rise high enough in the anticline to give the requisite head, the latter being presumably due to pressure transmitted to the water in the sandstone from overlying porous formations in the domes of the anticline. The second instance is in Beaver County, Pennsylvania. The wells are situated high up on the flank of the Fredrickstown anticline. The water comes from depths of less than 100 feet, and overflows between the drive pipe and the casing of the wells, the head being due to pressure transmitted from more superficial formations in near-by hills. Analogous instances of transmitted pressure were cited from Niagara limestone wells in Indiana.

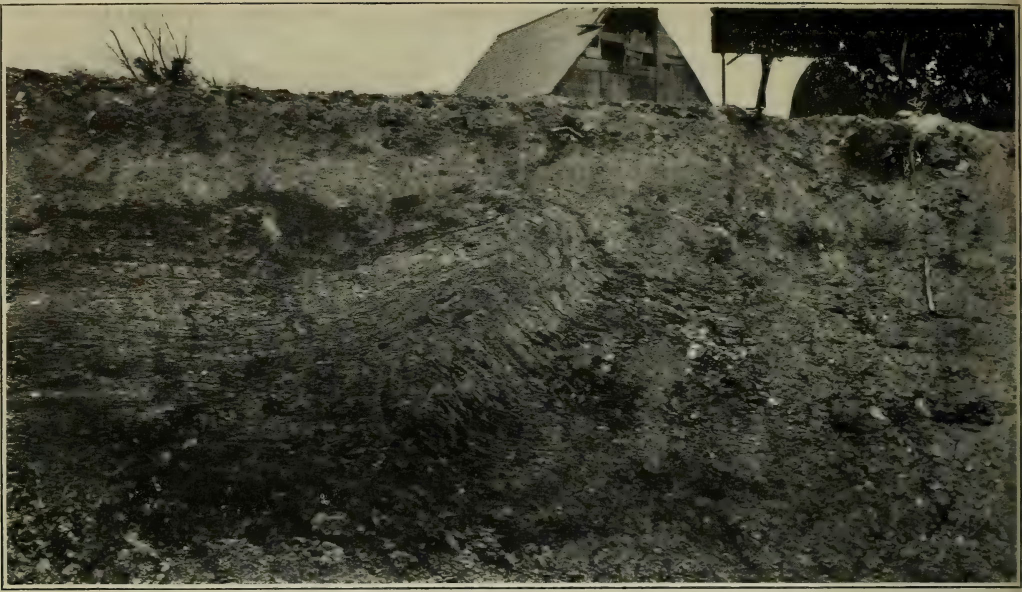

FIGURE 1.—UNSYMMETRICAL ANTICLINE WITH BOTTOM LAYERS HORIZONTAL

Eight feet of shale are covered by 2 feet of glacial drift. Photograph by Frank R. Van Horn.

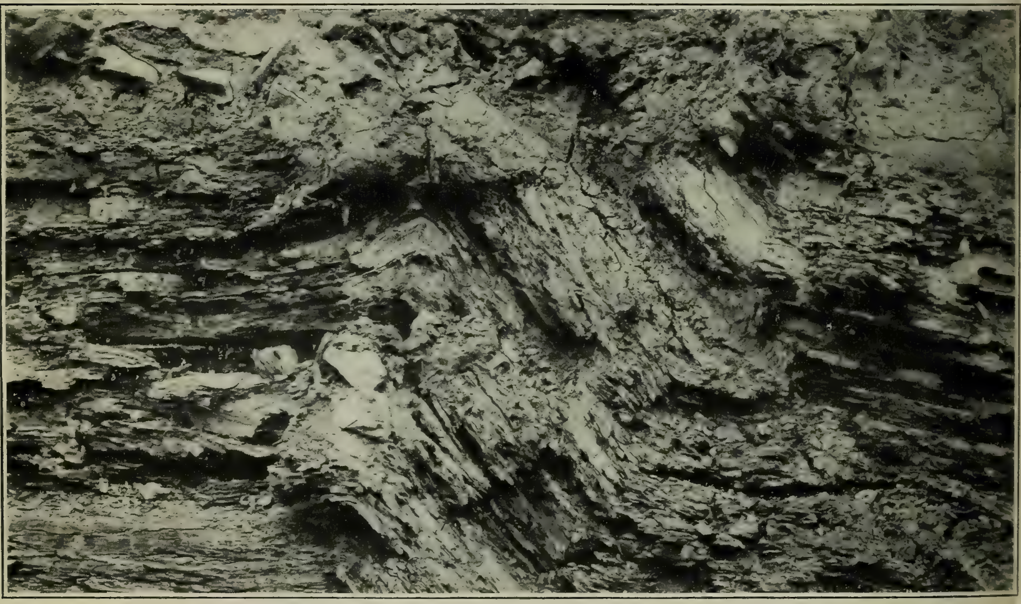

FIGURE 2.—UNSYMMETRICAL ANTICLINE

This shows 5 feet of disturbed shale overlain by 2 feet of glacial drift. Photograph by Frank R. Van Horn.

LOCAL ANTICLINES IN CHAGRIN SHALES AT CLEVELAND, OHIO

LOCAL ANTICLINES IN THE CHAGRIN SHALES AT CLEVELAND, OHIO

BY FRANK R. VAN HORN

(*Abstract*)

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Introduction and local Geology

In April, 1909, operations were begun in the eastern limits of Cleveland on the construction of the new Belt Line Railroad. Its tracks lie beside those of the New York, Chicago and Saint Louis Railroad for several miles, and both roads agreed to abolish many grade crossings. Their plans called for an excavation wide enough for four tracks between Cedar Avenue and Mayfield Road, a distance of nearly a mile. The cut is from 10 to 20 feet deep and the material consists of from 2 to 3 feet of glacial drift, mostly sand and gravel, while the remainder is Chagrin (formerly called Erie) shale. This is of upper Devonian age and is quite thinly bedded. At the surface the shale is invariably yellow from the formation of limonite, but below the line of normal weathering it possesses a slate blue color. The shale often contains concretionary masses known as clay ironstone, as well as masses of iron sulfide, generally in the form of pyrite, although marcasite may sometimes be present. It seems probable that the nucleus of the ironstone masses is also iron sulfide. When exposed to the air the shale, although originally often very hard, disintegrates rapidly into a tough, plastic clay, and is used quite extensively around Cleveland for the manufacture of vitrified brick and paving blocks. At times the shale contains sandstone layers which vary both as to their number and thickness.

Description of the Anticlines

Along the banks of this newly excavated cut many anticlinal folds were observed, particularly between Cornell and Mayfield Roads on the east and between Adelbert Road and Cedar Avenue on the west. The flexures were generally unsymmetrical, with limbs varying from 3 to 10 feet in length. In one case a monocline was noticed, but with this exception all folds belonged to the anticlinal type, no synclines being observed. The disturbance of the strata never extended more than 15 feet below the surface, and always passed into horizontal shale at the bottom and sides of the anticlines. Furthermore, the movement never, except in one case, extended to the opposite side of the cut. This shows that the anticlinal axis pitched rapidly and disappeared in the horizontal shale. In the one exception just mentioned the limbs of the folds on the opposite sides of the cut had no apparent relation to each other, except that a disturbance of the shale took place along the same general axis.

Probable Causes of the Flexures

The general observations mentioned previously indicate that the anticlines were always of local origin, and that the direction of motion was vertically upward and was located not far below the surface. In all cases the folds were below the limits of frost action, and were also generally below the zone of normal surface weathering. This was shown by the fact that the anticlines often extended into the blue unaltered shale. In several cases where the flexed strata were traceable for a vertical distance of 10 feet, 2 to 3 feet at the bottom were found to occur in blue shale, while the remainder was stained yellow from the oxidation of iron. It is evident that the various folds have no connection with each other, and therefore are not due to secular movements of the earth's crust. The anticlines must, therefore, have been formed by local pressures which were caused by some force inherent to the shales. Analyses of the Chagrin shales from various places in the vicinity of Cleveland show that sulphur is always present in smaller or larger amounts. Such an analysis, although not complete, is given from Chagrin shale used by the John Kline & Son Brick Company as follows:

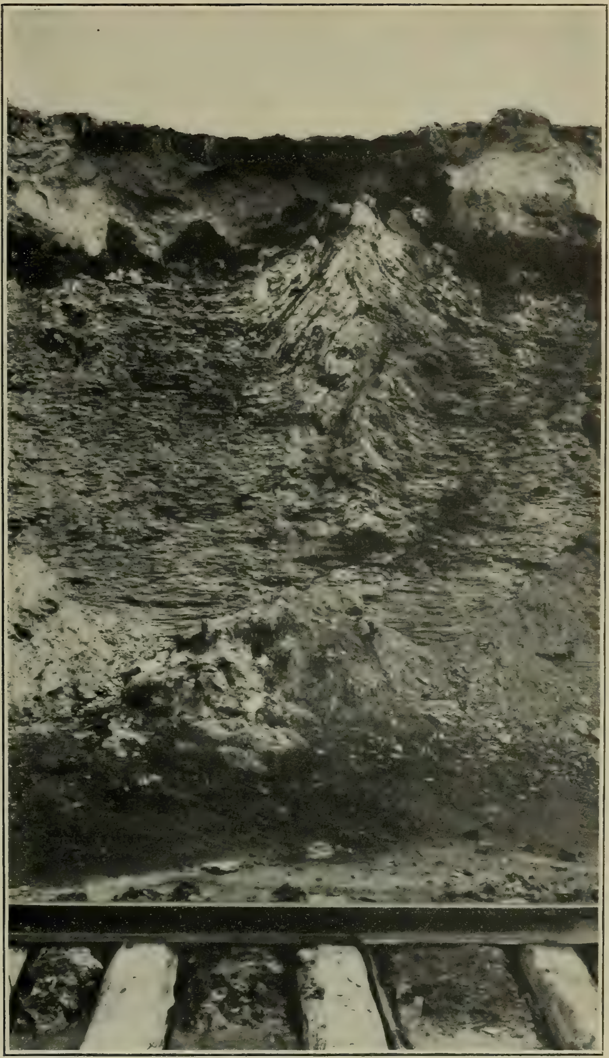
SiO_2	57.80
Al_2O_3	21.11
Fe_2O_3	5.80
MgO	1.73
CaO	0.80
Na_2O / K_2O	2.95
H_2O	6.01
SO_3	1.22
	97.42

The sulphur is undoubtedly present in the form of iron sulfide as pyrite, or possibly marcasite. As was previously stated, concretions or local enrichment of these minerals and clay ironstones are often present in these shales. It might have been possible that the force which caused the formation of the concretions or of concretionary layers could have exerted enough upward pressure to form the anticlines, or at least to aid in their formation.

The writer, however, is inclined to believe that the sulfides have been somewhat concentrated at various points by concretionary action. They have then altered to iron sulfate, and have thereby so increased in volume that local pressures have been produced, which in turn have flexed the shale. The specific gravity of marcasite and pyrite ranges from 4.85 to 5.10, while that of ferrous sulfate varies from 1.79 to 1.90. It is possible that an iron alum might have been formed at the same time, but the specific gravity would be about the same as that of the iron sulfate. The change from iron sulfide to iron sulfate or alum would therefore require nearly a threefold increase in volume which might well produce sufficient force to upheave the strata into anticlinal folds. In several places the formation of copperas and alum-like compounds was observed. The rapid weathering of the shales soon destroys all traces of structure, so that at the present writing, which is over a year after the anticlines were first observed, few, if any, are noticeable on the surface.

Conclusion

The local anticlines observed in the Chagrin shales were probably caused by pressure due to the nearly threefold increase in volume which results when iron sulfides alter to iron sulfate and alum-like compounds. The anticlines



ANTICLINE IN CHAGRIN SHALE

This view shows 3 feet of glacial sand and 5 feet of folded iron-stained shale having 3 well defined concretionary ironstone bands, 3 feet of blue shale with less folding, and 3 feet of horizontal shale. Photograph by Frank R. Van Horn.

probably occur at points where the sulfides were more concentrated by concretionary action.

DISCUSSION

Prof. H. L. FAIRCHILD: The photographs shown by Professor Van Horn of folding in the shales at Cleveland might be taken as illustrations of similar crushing in the Rochester shales in the Rochester district. The superficial Rochester shales are frequently crumpled, with some compression faulting. The suggestion of expansion due to hydration of sulfides does not apply here, as the shales do not contain any perceptible amount of unoxidized minerals.

Mr. J. L. RICH: In the Cretaceous shales of southwestern Wyoming a small anticline similar to that just described was observed. The shales underneath were entirely undisturbed. The anticline was sharp in the lower part, and gradually merged above into undisturbed shale. It was observed in a small stream gorge in the middle of a wide valley, a mile or more from any high land and in a region entirely unglaciated. No marked signs of the decay of pyrite or similar minerals was noted.

EXPERIMENTAL INVESTIGATION INTO THE FLOW OF DIABASE

BY FRANK D. ADAMS

(*Abstract*)

The author mentioned that the results of an investigation into the flow of marble had been presented to the Society at the Montreal meeting, and that since that time the investigation into the flow of rocks had been continued under a grant from the Carnegie Institution of Washington, the work having been extended to a study of impure limestones, dolomites, and various silicate rocks. He then gave the results of an experimental study of the deformation of a typical diabase. This deformation had been carried out at various pressures and at temperatures ranging as high as 1,000 degrees Centigrade. It was shown by means of lantern slides that the diabase at temperatures of about 450 degrees Centigrade was deformed with the development of the typical cataclastic structure, the structure exactly resembling that of certain varieties of flaser gabbro. The rock, furthermore, was not crushed to a powder during the process, but remained throughout solid and compact, and was found after deformation to have a crushing strength approximately one-half as great as that of the original diabase. It was shown that the structure of the deformed rock was identical with that seen not only in flaser gabbro, as above mentioned. but in many other foliated rocks whose structure had been impressed on them by movements in the earth's crust.

COON BUTTE AND METEORITIC FALLS OF THE DESERT[9]

BY CHARLES R. KEYES

(*Abstract*)

Coon Butte is regarded as only one of the many manifestations of the explosive type of vulcanism so prevalent in eastern Arizona. The apparently

[9] Read by title, in the absence of the author.

unusual abundance of meteoritic material in its vicinity is shown to be not an exceptional phenomenon, but rather a characteristic of desert regions. On account of the excessive dryness of the atmosphere there is practically no chemical decomposition of the rocks going on to destroy rapidly stony or metallic substances, no vegetation in which the larger meteoritic fragments are lost to view, and extensive deflation constantly keeps the immediate surface of the ground remarkably free of the lighter soils, leaving the pebbles and larger rock fragments always exposed to the sky. From the desert regions of the globe, it is believed, will be derived our chief information concerning meteoritic materials.

CONNATE WATERS OF THE ATLANTIC COAST

BY ALFRED C. LANE

(Abstract)

In previous papers before this Society, the Lake Superior and Canadian Mining Institutes, the author has called attention to the possibility of admixtures of connate (originally buried) waters in underground waters, especially in the Lake Superior region. Waters of the Atlantic coast seem also to show such admixture, sometimes of water higher in calcium chloride than the present ocean. For instance (figures in parts per thousand):

1. Maine, Vinalhaven: Ca .404; Mg .131; Na .465; K .140; SO_4 .122; Cl 1.790; Na:Cl .26.

2. Massachusetts, Boston: Ca 1.84; Mg .76; Na 3.38; K .07; SO_4 1.35; Cl 10.82; Na:Cl .31.

3. New Jersey, Passaic: Ca 1.72; Mg .74; Na 2.74; K .50; SO_4 1.55; Cl 8.50; Na:Cl .32.

1. Is cited from Clapp, United States Geological Survey W. S. Paper 223, well 230 feet deep.

2. Slide rule computation from Proceedings of the Boston Society of Natural History, New Hampshire, volume 17, pages 486-488, well 1,750 feet deep.

3. New Jersey Geological Survey Annual Report 1882, page 144, 2,050 feet, "wholly Triassic sandstone and shale."

CHANGES PRODUCED ON SPRINGS BY A SINKING WATER TABLE

BY T. C. HOPKINS

(Abstract)

The past two seasons (1908 and 1909) have been exceptionally dry in central New York. The water table has consequently sunk lower than for many years. Besides the drying up of many springs, wells, and streams, some of them have changed the kind of mineral matter held in solution. A spring at Edwards Falls, near Manlius, was a calcareous spring until last year when it gave off considerable sulphur. This year it is giving off both sulphur and iron oxide. Another spring 4 miles south of Syracuse has changed from a calcareous to a sulphur spring during the same time.

CRITERIA FOR THE RECOGNITION OF VARIOUS TYPES OF SAND GRAINS

BY W. H. SHERZER

Published as pages 625-662 of this volume.

DISCUSSION

Prof. J. BARRELL: I have listened with great interest and instruction to Professor Sherzer's paper, since the determination of the geographic and climatic conditions under which ancient sandstones were deposited, as indicated by the character of the grains, is a problem which in the progress of more exact knowledge must become of great importance. Several queries arise, however, at the present time in regard to the degree of security of conclusions based on the studies concerning modern sands which have thus far been recorded and which are used as a basis for interpreting the past.

First, the character of sands accumulated through wind, current, and wave action vary widely within themselves, depending on the duration and intensity of the several forces of accumulation. Complexities also enter into the problem through the concurrence of more than one agency at work and the previous nature of the material which has been acted on. To learn the limits of these modifying conditions hundreds of examples of modern sands should be studied, sands collected from type localities where the conditions of accumulation can be well determined. The distinctions now drawn from modern sands and applied to those of ancient origin are based on relatively few examples. May not therefore the distinctions appear sharper and safer than they really are?

Second, in such studies as are needed of typical sands efforts should be made toward quantitative determinations of various characteristics, so as to minimize as much as possible the personal equation in deciding on such indefinite qualities as roundness and smoothness of grains, especially as these qualities vary widely among the individual grains of any one sample. Measurements of the minimum size of rounded grains have been made, but these are not enough. A suggestion in this direction may be taken from a method of separating slate from coal devised, I believe, by the late Eckley B. Coxe, of Drifton, Pennsylvania. The coefficient of friction depends on the shape of the fragment and the smoothness of the surface. Fragments of a uniform size coming from the screen are allowed to slide down a sheet-iron trough with a slot at the bottom. The coal fragments, sliding and rolling faster, are able to jump this slot; the slate, sliding more slowly, drops through. Similarly, a quartz sand could be separated into sizes by sieves and each size subjected to various processes to determine the percentage of different forms. In applying such methods to ancient sands, however, such adaptations would have to be made as would allow for secondary growths and permit microscopic determinations, but decomposed portions of beds might give sands which could be directly compared.

Third, some emphasis is given to the preceding points by the consideration of a little-known paper by A. R. Hunt, published in 1887 in the "Report and Transactions of the Devonshire Association," pages 498-515. He finds on the Skerries Shoal that many of the grains of quartz sand are well rounded down to the minimum diameter of one-eightieth of an inch, materials below this size being removed. The unusual roundness of these wave-worn sands he accounts for through the cooperation of tidal and wave action holding them on the shoal and subjecting them to continual wear. By the cooperation of waves and currents he concludes that such wear may extend broadly to a depth of as much as 40 fathoms. This raises the question as to the limit of fineness and roundness of grains which might be attained on the bottom of an epicontinental sea, everywhere shallow and to which sand was the dominant material supplied. The conditions are quite different from the common cases of river and beach action.

Fourth, it is well known that along the flat sandy coasts of humid lands, such as much of the Atlantic coast of the United States, wind action plays an important part in moving and wearing the sands which have but recently been transported by wave action, and much of these wind driven sands may again become portions of marine deposits. To what extent, therefore, in a slow and oscillating marine movement across baseleveled lands may eolian action cooperate in shaping the grains of sand independently of the climate? At the present time eolian action in deserts is an agency of first importance and marine oscillations across sandy plains are at a minimum. In those epochs, however, when the latter was a widespread and characteristic geologic activity, is there not danger of a too hasty inference as to the existence of an arid climate based upon evidence of eolian action in the wear of the sand grains?

For example, two decades before the British geologists began the study of the significance of this subject Logan noted, in 1863, the rounded character of the sand grains in the Potsdam sandstone, a formation which is regarded as a typical example of a slow marine transgression of a baseleveled land.

Consequently, in view of these queries, although valuable and suggestive as the studies of ancient sand grains have shown themselves to be, there is, however, apparently need of more exhaustive study of modern sands accumulated under determined conditions in order to apply that knowledge with greater precision to the past.

Prof. W. M. Davis: I wish to suggest that in collecting specimens of sand it is desirable to indicate the distance of transportation during which the sand has been under the action of the agency concerned; also that it would be well to use a higher magnifying power, sufficient to show the texture of fractured or frosted surfaces as well as the general form of the grains.

Prof. A. C. Lane: Referring to Professor Barrell's remarks, I think it is not so much a question of "transgression" as transportation along shore, like the Florida deposit cited. Having had occasion, also, to study the Sylvania, I am inclined to differ from Professor Sherzer somewhat in emphasis. I agree with him that part of the Sylvania is waterlaid with its dolimitic cement; that in places it is eolian, and that the climate was arid, but I am inclined to lay more stress on derivation from a previously fairly concentrated quartz sandstone by transportation along shore some distance as a factor in the peculiar character of the Sylvania.

THE THEORY OF ISOSTACY

BY W. M. DAVIS

(*Abstract*)

1. Let it be assumed that the crust of the earth is too rigid to be affected by the forces involved in isostacy, and that it has been deformed only by other and stronger forces, acting in different epochs, over various areas, at unequal rates, and with unlike intensities. Under this assumption the facts that have been accounted for by isostacy may be explained by the accidental agreement of depression and deposition, while certain other facts, such as the formation of great trough valleys or the depression of land areas under deep ocean water, for which isostacy gives no adequate explanation, may be accounted for by disagreement between deformation and deposition. A merely accidental agreement between depression and deposition is not improbable, for small and slow movements excite small and slow transfer of materials, while large and rapid movements excite great and active transfer of materials.

2. The initiation of isostatic movement involves a non-isostatic movement. The cessation of isostatic movement by the reversal of depression to elevation or of elevation to depression has occurred under so many different conditions as to structure and area, and especially as to load, that isostacy must have a very subordinate value in the total movement.

3. The peneplanation of mountains of various structures and at many different dates has involved a long-maintained stability of extensive regions, while they were suffering prolonged erosion and great loss of weight. After degradation, some peneplains have been depressed and buried, others elevated and dissected. All of this is inconsistent with isostacy.

Discussion

Prof. H. F. Reid: I am in entire accord with Professor Davis's ideas. There are so many vertical movements of the crust that can not be due to the simple restoration of isostatic equilibrium that it seems very doubtful if any movements can be definitely assigned to that cause. Gravity observations show that there is general isostatic equilibrium between the ocean beds and the continents; but islands in the ocean are held up by the rigidity of the crust, and the series of transcontinental gravity measurements made some years ago and discussed by Mr. Putnam and Mr. Gilbert show that areas like the Appalachian Mountains and the Rocky Mountains do not owe their altitudes to isostatic equilibrium.

GEOLOGICAL PROGRESS MAP OF OKLAHOMA

BY CHARLES N. GOULD

(*Abstract*)

With the possible exception of Triassic and Jurassic formations, Oklahoma contains rocks of every geological age above the Lower Cambrian. Pre-Cambrian granites and Lower Paleozoic sediments are exposed in the four mountain regions, namely, the Wichita, Arbuckle, Ouachita, and Ozark.

Three-fourths of the state is occupied by rocks of either Pennsylvanian or Permian age, the former being approximately 15,000 feet thick and the latter from 3,000 to 4,000 feet thick. Cretaceous rocks outcrop in southern and western Oklahoma and Tertiary deposits occur on the high plains in the western part of the State. Among the important problems yet to be solved are the following:

Petrology of the igneous rocks.
Paleontology of the Ordovician formations.
Age of the Woodford chert.
Relations of the Standley and Jackfork formations.
Cause of the thickening of the Pennsylvanian sediments southward.
Source of the Pennsylvanian and Permian sediments.
Origin of the iron in the Red beds.
Origin of the gypsum.
Age of Cretaceous outlayers in western Oklahoma.
Origin of the sand hills.

OBSERVATIONS ON RATE OF SEA-CLIFF EROSION

BY CHARLES P. BERKEY

(Abstract)

Certain cliffs of unconsolidated materials along the Atlantic coast bear evidence of comparatively rapid erosion. Reliable measurements, however, are rare. Nearly all available data are estimates or generalities, based on the destructive effects of some exceptionally severe storm. For the past year a locality where such erosion prevails has been kept under observation. Measurements have been made as often as any pronounced effect was observed. The accumulated data are summarized, and their bearing on the question of rate of cliff retreat is indicated.

CLIMATE AND PHYSICAL CONDITIONS OF THE KEEWATIN

BY A. P. COLEMAN

(Abstract)

Glacial conditions prevailed at the beginning of the Huronian, but hitherto less has been known of the climate of the Keewatin. It is often referred to as essentially eruptive and with very different conditions from the present—hot seas, etcetera. In Ontario, where the Keewatin is best displayed, it often includes thousands of feet of ordinary sediments, not only the puzzling iron formation, but carbonaceous slate, ordinary slate, arkose, sedimentary mica schist and gneiss, and crystalline limestone. The extent and character of these sediments are such as correspond to ordinary weathering on a land surface. They have often the composition of a clayey sand, such as could not be furnished by volcanic products, though there may have been submarine eruptions then, as now. The eastern Grenville series, in part probably equivalent to the Keewatin, includes similar rocks, but with far more limestone. It is essentially a sedimentary series. Most of the eruptives of the Keewatin are surface volcanics or ash rocks. The sedimentary rocks imply land and

sea, cool waters in which life existed, and in general climates and conditions like the present. As these are the oldest known rocks, there is no geological evidence that the surface of the earth was ever too hot to allow water and life to exist. Geologists and astronomers should bear this in mind in their theories.

PERMO-CARBONIC CONGLOMERATES OF SOUTH BRAZIL

BY J. B. WOODWORTH

(*Abstract*)

The boulder-bearing Permian beds of South Brazil for which Derby proposed a glacial origin in 1888, sagaciously likening them to the deposits of India, were searched in 1908 for evidences of glaciation not previously found. Striated stones, including probable fragments of disrupted glaciated floors, were found in tillite beds on the Rio Jaguaricatu in northern Paraná, and similar phenomena, especially striated stones, in the states of São Paulo and Santa Catharina. Much of the boulder-bearing group demands floating ice at sea-level, as shown by a depauperated marine fauna between boulder beds in the valley of the Rio Negro. Certain tillite beds seem best explained as ice-laid deposits derived from an easterly source through ice action capable of disrupting and transporting seaward certain readily recognized rocks of the series inferior to the glacial beds. The paper (a part of the results of the First Shaler Memorial Expedition) was illustrated by stereopticon views showing the geology and topography of the area.

Discussion

Dr. I. C. White: It is needless to say that it gives me extreme pleasure to learn that Professor Woodworth has found the missing link, namely, ice-scratched boulders, in the Permian conglomerates of South Brazil, which demonstrates fully their glacial origin.

When I discovered these deposits in 1905, and announced their glacial origin in a paper read before this Society at the Philadelphia meeting in December, 1906, I was certain that they were true glacial deposits, although I failed to find the old glacial striated floor, or striated boulders. However, the structureless tillite filled with enormous granite blocks, 40 miles distant from any outcrop of granite, left no doubt in my mind of the existence of a glacial epoch during Permian time in South Brazil, corresponding perfectly with that which has been proven for South Africa. Many details of boulder deposits, etcetera, are given in my final report on the coal fields of South Brazil published last year.

As confirmatory of the existence of a glacial epoch in Brazil during Permian time, it is of great interest to know that Dr. David White arrived at this same conclusion independently from a study of the collection of fossil plants which I made and sent him before I had communicated to him my own conclusions as to the existence of glacial deposits in that region.

Concerning the name "Orleans," to which Professor Woodworth has made reference, I would say that it was never entirely satisfactory to me, and Professor Woodworth has my willing consent to change it to a more suitable term. Since these deposits are very conspicuous along the waters of Rio Negro, that or some other name could be given.

MAGOTHY FORMATION OF THE ATLANTIC COAST[10]

BY A. B. BIBBINS

(*Abstract*)

So far as Long Island is concerned, the paper will regard the Magothy as present in force, its contact with the Raritan (of land as now defined) lying along the north shore of the western half of the island. The upper limits of the formation, which are so well defined to the southward, may prove more difficult to determine here, owing to the fact that the superjacent Matawan and its overlying formations appear to have taken on, along with their marked change in strike, Magothy-like characters, as, indeed, the Matawan has already begun to do as far south as Atlantic Highlands. The greensands of the upper portion of the Melville section and those of the deep wells toward the eastern end of the island will probably prove to lie even higher than the Matawan, but the most impressive feature of the Long Island well and other sections along the belt where the greensand marls might be expected is the almost universal absence of glauconite beds, and the occurrence in their stead of materials lithologically similar to those of the subjacent Magothy—indicating either more moderate depths during sedimentation than those of their contemporaneous deposits to the southward, or other changes of conditions which brought different sediments and largely eliminated foraminifera. The thickness of the Magothy beds on Long Island seems likely to reach considerably more than 100 feet. It is certain that the formation thickens rapidly toward the northward across New Jersey to a maximum of 100 feet on the south shore of Raritan Bay. The Magothy is an important physiographic factor. Its influence as a bay, island, hill, and drainage-line former is impressively shown all along our coast. As an economic factor one finds that one of the greatest series of sand quarries in the world—on the west shore of Hempstead Harbor, L. I.—an important source of building sand for Greater New York, lies to a goodly extent in the Magothy formation, while the very general arenaceous lithology and loose bedding of the formation render it an important underground water-bearer.

AGE OF THE CALCIFEROUS FORMATION OF THE MOHAWK VALLEY, NEW YORK

BY E. O. ULRICH AND H. P. CUSHING

(*Abstract*)

The Little Falls dolomite of the Mohawk Valley is found to consist of two distinct and unconformable formations. The lower and thicker of these is a dolomite formation which, in the eastern sections, is underlaid by the Potsdam sandstone, and the two grade into one another through passage beds. To the west the Potsdam and passage beds disappear and the dolomite rests directly on the pre-Cambrian. This dolomite the authors regard as of Saratogan (Ozarkian) age. They have traced it into the Champlain Valley, and find that it there constitutes division A and the lower half of division B of the Beekmantown (Calciferous) formation, as characterized by Brainerd and Seely.

[10] Read by title, in the absence of the author.

The upper of the two formations on the Mohawk is a limestone formation, which has heretofore uniformly been described as the "Fucoidal beds" of the Calciferous. It contains a considerable fauna which has been described by Cleland. The authors regard it as of Beekmantown age and as representing the lowest known division of the New York Beekmantown. The fauna has not as yet been recognized in the Champlain Valley, and the formation, if present there, is represented by the upper portion of division B. The authors are proposing for this formation the name of the Tribes Hill limestone, and restrict the name Little Falls dolomite to the lower dolomite formation.

About Saratoga is a very local representation of a very fossiliferous limestone, well known as the source of the Cambrian fauna described by Walcott. This seems to us to be on the horizon of the lower portion of the Little Falls dolomite and to represent a more offshore phase of that formation.

The authors find everywhere an unconformity at the summit of the Little Falls dolomite, both in the Mohawk and Champlain Valleys. They regard this as the proper boundary between the Saratogan and Beekmantown—between the Cambrian and Ordovician of present-day classification. This gives, in New York at least, a prominent unconformity between the two systems, instead of a gradation of one into the other.

The complete paper is published in New York State Museum Bulletin 140, pages 97-140.

UPPER CAYUGAN OF MARYLAND

BY T. POOLE MAYNARD

(Abstract)

The upper Cayugan of Maryland occurs in two well defined areas in the western part of the state, the Hancock and Cumberland areas, and crosses the state in a northeast-southwest direction, following the general trend of the Appalachians. The rocks constituting the upper Cayugan consist usually of argillaceous, thin-bedded limestones at the bottom, passing gradually into the heavier-bedded limestones of the lower Helderberg. These limestones lie between the Salina below and the Coeymans above and have an average thickness of 110 feet. There is only a gradual change in lithology from the Salina to the Coeymans and no well defined lithological break exists. The upper and lower limits of the rocks constituting the upper Cayugan are determined on paleontological grounds. These rocks, while equivalent in Maryland to the Manlius and Cobleskill of New York, can not be subdivided in Maryland either on paleontological or lithological grounds. The Rondout is absent in Maryland, while the fauna of the Cobleskill and Manlius are not distinct and separate as they are in New York, but they intermingle, typical New York Manlius and Cobleskill forms occurring together. They are also associated with forms occurring in the upper Decker Ferry of New Jersey.

Discussion

Prof. A. W. Grabau urged the abandonment of the name Cayugan and the substitution of the term Monroe; also the abandonment of the term Salina as referred to the Maryland section, and the substitution of some other name.

STRATIGRAPHIC RELATIONS OF THE LIVINGSTON BEDS OF CENTRAL MONTANA

BY R. W. STONE AND W. R. CALVERT[11]

(*Abstract*)

The Livingston formation occurring at Livingston, Montana, has been described as resting unconformably on the Laramie and overlain by the Fort Union formation. Its age has been considered to be post-Laramie and it has been correlated with the Denver formation of Colorado, partly on lithologic similarity, both formations being composed largely of tufaceous beds. This paper shows that the Laramie of the Livingston and Little Belt Mountains folios of the Geological Atlas of the United States is Eagle, or at least lower Montana, and that there is no unconformity between it and the overlying Livingston beds in the area under discussion. It shows also that on the west and south sides of the Crazy Mountains about 7,000 feet of sediments, mainly andesitic tuffs, lying between the Eagle and Fort Union formations, constitute on lithologic grounds a single formation, but that on the north and east sides of the Crazy Mountains these same tufaceous beds are intercalated in the Colorado, Eagle, Claggett, Judith River, Bearpaw, "Laramie," and Fort Union formations. In other words, the Livingston has no formational value and has no definite age, for it represents volcanic activity which recurred throughout late Cretaceous and early Tertiary time.

DISCOVERY OF FOSSILS IN THE QUANTICO SLATE BELT, AND THE ASSOCIATION OF VOLCANO-SEDIMENTARY BEDS WITH THE SLATES OF THE VIRGINIA CRYSTALLINE REGION[12]

BY THOMAS L. WATSON AND S. L. POWELL

(*Abstract*)

Recent field studies of the various slate areas in the crystalline (Piedmont) region of Virginia by the State Geological Survey have resulted in much important information on the lithologic characters, structure, and age relations of the rocks. Of especial interest are (1) the discovery of fossils in the easternmost of the slate areas, and (2) the recognition of well defined volcano-sedimentary beds in intimate association with the slates in several of the most extensive areas. During the past season fossils were found a short distance north of Dumfries, Prince William County, Virginia, in the Quantico slate belt, which are shown to be closely related to Cincinnatian forms. In 1892 Mr. Darton announced the discovery of fossils in the Arvonia slates of Buckingham County, Virginia, which were determined by Mr. Walcott to be upper Ordovician. From the evidence of organic remains, these two areas, separated by a considerable distance, though aligned approximately on the same strike, are shown to be of the same age—Cincinnatian.

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[11] Introduced by M. R. Campbell

[12] Read by title, in the absence of the authors.

RHODE ISLAND COAL[13]

BY CHARLES W. BROWN

(*Abstract*)

Coal deposits in Rhode Island have been mined intermittently for the past 100 years and at various places—in regions about Providence, along the western edge of the Narragansett Basin, and at Portsmouth, in the central southern portion. The recent development of the Portsmouth coal mine has led to a careful study of the geology, extent, and testing of the fuel values and chemical condition of this coal. The coal beds are found in the lower members of the Carboniferous in Rhode Island. Former mining covered an extent of 4,000 feet along the strike and 1,200 feet or more down the dip.

The coal is extremely hard anthracite, having a grayish black color and bright luster, with some bone and more or less impurities of quartz and pyrite, becoming only graphitic along shear planes. It is found in beds averaging 2 or 3 feet, and occasionally in large "rolls" from 60 to 72 feet in diameter and 75 feet wide. The best coal is found in the rolls, the "vein" matter increasing as the bed becomes thinner.

Official tests show that the coal will burn and has a certain fuel value. By the proposed "chemical treatment" this value is supposed to be enhanced. The practical value of this treatment has not been officially determined. The variation in the thickness of the beds, together with unknown extent of the basin and possible increase or decrease of impurities, make final statement as to amount and value of coal beds impossible.

GEOLOGIC THERMOMETRY

BY FRED E. WRIGHT

(*Abstract*)

In ordinary thermometry, temperature is defined by the expansion of a perfect gas, and is expressed in terms of fixed units, determined by the freezing and boiling points of water under standard conditions. Temperatures are ascertained practically by means of thermometers which, although they differ greatly in type, are all based on some property which varies in a definite way with the temperature. In geology temperatures are of fundamental importance, particularly the temperature to which rocks were heated in past geologic ages and under inaccessible conditions. Points on the geologic thermometer scale must, therefore, be historical points, to be determined primarily by the permanent effects which such temperatures have produced on the rocks and rock components, and which are clearly marked even at lower temperatures. The factors which may serve to furnish points of this nature are, especially, melting temperatures of stable minerals and of eutectics, inversion temperatures of minerals, temperate limits beyond which monotropic forms can not exist under different conditions of pressure; stability ranges of enantiotropic forms and of minerals which dissociate or decompose at higher temperatures, and temperatures beyond which certain optical or physical properties

[13] Read by title, in the absence of the author.

are changed permanently. These factors can be and are being determined by modern laboratory methods, and are in turn directly applicable to the study of rocks. The data now available on the geologic thermometer scale indicate that the establishment of such a scale is feasible, and can be accomplished by a sufficient number of proper laboratory determinations.

Discussion

Prof. J. F. Kemp: Mr. Wright's ingenious application of the peculiar properties of quartz will be of great service in testing some of our conclusions hitherto reached regarding the bodies of magnetic iron ore in the ancient gneisses. In later years observers have more and more drifted away from the sedimentary conceptions of origin and have proved a direct crystallization from fusion. In the Adirondacks and elsewhere the ores are in quartzose rocks. If now the quartzes have been formed below 575° C., fusion, unless followed by complete metamorphism, is out of the question. But if the quartzes show the properties of the higher temperature the hypothesis of development from fusion will be corroborated. Mr. Wright has already consented to make some tests which will be of much significance.

OBSIDIAN FROM HRAFNTINNUHYGGUR, ICELAND

BY FRED E. WRIGHT

(*Abstract*)

Describes (*a*) peculiarly pitted surfaces on specimens of obsidian which resemble in a remarkable degree the markings of the Austrian moldavites; (*b*) also a unique type of crystallization in cavities in this obsidian.

PEGMATITE IN THE GRANITE OF QUINCY, MASSACHUSETTS

BY C. H. WARREN AND CHARLES PALACHE

(*Abstract*)

Only two important occurrences of pegmatite are known in the riebeckite granite of Quincy. These are exposed in two of the quarries and take the form of rudely cylindrical masses of considerable size entirely inclosed in the granite. In mineral composition they are closely similar to the granite, the essential minerals being quartz, alkali-feldspar, riebeckite, and ægirine; accessory minerals so far identified are fluorite, parisite, octahedrite, ilmenite, wulfenite, and the sulfides molybdenite, galena, sphalerite, and chalcopyrite. The pegmatites exhibit a certain symmetry of structure. Fine graphic-granite forms a marginal band, succeeded centrally by a zone of coarse granitic texture made up of quartz, feldspar, riebeckite, and ægirine-augite. As a rule, this zone graduates centrally into almost pure massive quartz, sometimes containing sulfides. In one portion of the largest mass the center is microlitic, and in the cavities thus formed the quartz, feldspar, and ægirine are well crystallized, while the rarer minerals noted above find there their principal development. Angular fragments of the pegmatite, inclosed in felted crocidolite, and deeply corroded crystals of riebeckite partly replaced by fluorite, point to a final stage of crushing and pneumatolytic action. The paper describes these deposits and the minerals in detail.

Discussion

Prof. J. F. Kemp remarked that the occurrences of ores like galenite as noted in the paper tend to confirm our conviction that many of the deposits of the ores have igneous sources.

ORIGIN OF THE ALKALINE ROCKS

BY R. A. DALY

Published as pages 87-118 of this volume.

Discussion

Prof. J. F. Kemp: Professor Daly's suggestion will be productive of much fruitful meditation. Nevertheless, from having seen several areas of nephelite syenite, I think we should be cautious in inferring the influence of the limestones now visible on magmatic differentiation. The observed relations are those of a later body of igneous rock cutting limestones and only exerting contact metamorphism, whereas for magmatic differentiation we must have the calcareous rocks in the depths adjacent to the internal reservoir. This would mean Archean limestones in most cases, and would place the matter beyond observation and in the realm of hypothesis.

COMPLEX OF ALKALINE IGNEOUS ROCKS AT CUTTINGSVILLE, VERMONT

BY J. W. EGGLESTON[14]

(Abstract)

This is an oval area of alkaline igneous rocks, stocklike, with roughly concentric arrangement and intrusive into gneisses. Syenite, with nepheline-bearing varieties, is the chief type. There is also much essexite. The mass is cut by numerous dikes, including tinguaite and camptonite. In chemical character the rocks are closely related to those of southern Norway, described by Brögger.

Discussion

Prof. J. E. Wolff: On the old geological map of Vermont a number of round or oval areas were marked in red as "granite." Of three of these, one in Stamford, Vermont, is a coarse granite of the rapakiwi variety; another is Ascutney Mountain, described by Daly as a complex of alkaline igneous rocks, and the third, also such a complex, as that at Cuttingsville.

Mr. J. A. Dresser: The Monteregian hills in southern Quebec are a series comparable to the Cuttingsville area, so well described by Mr. Eggleston. In these hills, which rise at intervals for 50 miles in an east and west line, there is a large development of essexite, accompanied by nepheline or alkali syenites. Their composition, as indicated by the relative amounts of essexite and syenite, grows less basic towards the eastern end of the series, and the Cuttingsville area seems to be still less basic than the easternmost of these. The central syenite seems to correspond most closely with the nordmarkite of Shefford

[14] Introduced by J. E. Wolff.

Mountain and the tinguaite with the tinguaite from Brones Mountain. These are the two most easterly hills of the Monteregian series.

BLEACHING OF GRANITE AT LIMESTONE CONTACTS

BY H. P. CUSHING

(*Abstract*)

In the Thousand Island region, on the New York side, there is a large representation of Grenville limestones, quartzites, and schists which are cut through and cut out by bathyliths of Laurentian granite gneiss. The ordinary color of the granite gneiss and of its dikes is red, but at limestone contacts the color changes to white, and all the granite dikes in the limestone are white. Both colors are unquestionably primary; in other words, the granite solidified as red granite except when affected by the limestone, and the field relations show plainly that it was some influence exerted on the granite by the limestone at the time of solidification that caused the color change.

The red color of the feldspar of the ordinary granite seems due to the presence of ferric oxide in free condition. It remained uncombined at the temperature of solidification. In the presence of calcium carbonate, however, it entered into combination, and into comparatively colorless combination. Experiments seem to show that it is the lime rather than the carbon dioxide which was efficacious in causing the change, but certainty has not been attained in the matter; nor is it at all certain what compound was formed.

This color change seems to us to suggest in some cases a comparatively simple method of determining approximately the temperature of solidification of granites. It also suggests a reason for the scarcity of lime-soda feldspars of red color.

BARITE DEPOSITS OF FIVE ISLANDS, NOVA SCOTIA[15]

BY CHARLES H. WARREN

(*Abstract*)

Barite deposits occur about 2 miles north of Five Islands, Nova Scotia, a village located 12 miles east of Parsboro, on the north shore of Minas Basin. The principal outcrops are on the steep banks of the bars and East River, and at isolated points between for a distance of some 2 miles. The barite is coarsely crystalline and remarkably pure. It occurs in the form of large, irregular, veinlike masses, usually with steep dip, associated stringers, and smaller isolated masses in an ancient fault breccia; also as a filling for fissures, sometimes several feet wide in the massive ledge rock. The fault breccia is part of an extended zone of faulting, frequently marked by brecciation and fissuring, which lies in a narrow east-west band of much folded Devonic slates and quartzites on the southern side of the Cobequid Hills. The fault zone follows rather closely the contact with intrusive syenites which form the core of the hills. Near the eastern end of the fault zone, north of Londonderry, barite also occurs associated with much ankerite and iron ore,

[15] Read by title by request of author, to expedite the programme.

also in a fault breccia. The barite is believed to have resulted from a leaching and concentration process which took place through the agency of water percolating downward along a zone of faulted and broken rock. The adjoining ledge rocks contain about 0.2 per cent BaO. A comparison with deposits elsewhere leads to the conclusion that many barite occurrences are the result of a concentrating of the barium content of limestones, sandstones, and quartzites wherever faulting or crushing has made an easy channel for percolating waters.

FAYALITE IN THE GRANITE OF ROCKPORT, MASSACHUSETTS

BY CHARLES PALACHE

(*Abstract*)

A recent discovery of large crystals of fayalite in a granite pegmatite near Rockport furnishes for the first time opportunity for an accurate description of this interesting mineral occurrence, the mineral having been twice before found here, but in neither case studied in place.

NELSONITE, A NEW ROCK TYPE: ITS OCCURRENCE, ASSOCIATION, AND COMPOSITION[16]

BY THOMAS L. WATSON AND STEPHEN TABER

(*Abstract*)

Nelsonite is the name given to a new rock type occurring in dikelike bodies in the foothills region of the Blue Ridge in Nelson and Amherst counties, Virginia. It forms one of the rock types of a comagmatic area, the rocks of which are characterized chemically by high titanium and phosphorus. Variation in mineral composition gives rise to several different facies of the nelsonite, the normal one of which is an even granular mixture of essentially ilmenite and apatite, with or without rutile. At several localities ilmenite is replaced by rutile, and the rock is composed chiefly of rutile and apatite with some ilmenite. Green hornblende is occasionally present. The ratio of titanium minerals to apatite is variable, ranging from a rock composed largely of the dark minerals with but little apatite to occasionally a rock composed of nearly all apatite. Magnetite replaces the titanium minerals in some of the dikes, accompanied by biotite and apatite. A second pronounced facies of the rock is observed over parts of the area, which shows a predominance of the dark ferromagnesian minerals, more especially hornblende, over the ore minerals. This variety of the rock is composed chiefly of hornblende, less apatite, and some ilmenite or magnetite. Chemical analyses of the rocks are given and their position in the quantitative system of classification of igneous rocks computed and shown.

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[16] Read by title, in the absence of the authors.

REGIONAL DEVOLATILIZATION OF COAL[17]

BY DAVID WHITE

(*Abstract*)

Regional progressive devolatilization, which marks the second (dynamochemical) stage of coal formation, is due in most areas to deep-seated horizontal thrust pressure long continued. Essentially it is regional metamorphism, coal being a most sensitive index. Effects of loading and faulting. Comparison of effects of intrusives.

MICROSCOPIC STUDY OF CERTAIN COALS IN RELATION TO THE SAPROPELIC HYPOTHESIS

BY E. C. JEFFREY[18]

(*Abstract*)

Discussed the ingredient matter and relation of the same to formation of cannels, kerosene shales, bogheads, etcetera. Evidence against algal hypothesis as accounting for special characters.

PRESENT AND FUTURE OF NATURAL GAS FIELDS IN THE NORTHERN APPALACHIANS

BY F. G. CLAPP

(*Abstract*)

The waning natural gas supply in some fields brings up the question as to the future of the natural gas business, and this paper is a summary of the conditions in the eastern fields of the United States. While the writer admits that the outlook is in some ways discouraging, he believes, nevertheless, judging from predominant indications, that new wells and new fields will continue to be found and be productive for many years yet. During the year 1909 there was improvement and increase in the business and in the total area of the productive fields in Pennsylvania and West Virginia. In that year the mains of the principal producing companies were greatly extended. Cincinnati and many smaller communities, which never before had natural gas, are now supplied. This paper describes several new fields of interest in Pennsylvania, West Virginia, and Ohio, and explains their relation to the geological structure. Most of the shallow sand fields, which were exhausted years ago, have been recently replaced by adjacent or subjacent new fields in deeper sands. In all cases so far examined by the writer these fields bear a constant relation geologically to each other and to the structure.

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[17] Read by title, in the absence of the author.
[18] Introduced by David White.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 21, PP. 789-796 DECEMBER 31, 1910

PROCEEDINGS OF THE ELEVENTH ANNUAL MEETING OF THE CORDILLERAN SECTION OF THE GEOLOGICAL SOCIETY OF AMERICA, HELD AT BERKELEY, CALIFORNIA, MARCH 25 AND 26, 1910

BY GEORGE D. LOUDERBACK, *Secretary*

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SESSION OF FRIDAY, MARCH 25

The eleventh annual meeting of the Cordilleran Section of the Geological Society of America was called to order in room 35, South Hall, University of California, Berkeley, at 10.30 a. m., March 25, 1910, by the chairman of the section, Prof. A. C. Lawson.

The minutes of the previous annual meeting were read and approved, except that "ninth" annual was ordered changed to "tenth" annual, the ninth annual meeting having been held at Albuquerque, New Mexico, in conjunction with the general Society.

ELECTION OF OFFICERS

The officers of the section were reelected for the ensuing year: A. C. Lawson, Chairman; G. D. Louderback, Secretary; G. K. Gilbert, Councilor.

The section then passed to the reading of scientific papers, and the following were presented in the order given:

LIMESTONE PLAINS OF THE INTERIOR OF BAHIA

BY J. C. BRANNER

(*Abstract*)

Limestones, probably of Jurassic age, cover many thousands of square miles in the interior of Brazil, especially in the states of Bahia and Minas Geraes. In many parts of the same region valley floors are covered by recent limestone deposits spread out in horizontal sheets. These later limestones appear to be derived from the older ones by processes now in operation in the same region in modified form.

The paper was discussed by A. C. Lawson, who compared the phenomena described with some in Mexico; by E. W. Hilgard, with reference to the Santa Cruz Mountains and Susan River Valley, and by E. Kelsey.

GEOLOGIC WORK OF ANTS IN TROPICAL COUNTRIES

BY J. C. BRANNER

Published as pages 449 to 496 of this volume.

The paper was discussed by E. W. Hilgard, with special reference to the "hog wallows" of Louisiana, which he considers may possibly have been caused by the action of ants, although believing that "hog wallows" in general—and especially in the west—are the products of wind action, erosion, etcetera. E. Kelsey also remarked that similar phenomena could be caused by the blowing down and uprooting of trees.

TABLES FOR THE DETERMINATION OF CRYSTAL CLASSES[1]

BY W. S. TANGIER SMITH

Published as pages 731-736 of this volume.

[1] This paper, in the absence of the author, was read and discussed by A. S. Eakle.

The meeting then adjourned for the noon recess.

The afternoon session was called to order at 1.30 p. m., in room 22, South Hall, and the following papers were read and discussed:

OCCURRENCE OF THE HALOGEN SALTS OF SILVER AT TONOPAH, NEVADA

BY J. A. BURGESS AND A. S. EAKLE

NEW DEVELOPMENT AT THE MOUTH OF THE MISSISSIPPI

BY E. W. HILGARD

(*Abstract*)

This refers to the uprising of a serious obstacle to navigation outside of the Eads jetties in the South Pass, which has been made the main outlet of the Mississippi and of navigation, on account of its being the only one of the Mississippi mouths showing no mud-lump activity. The author predicted, however, in 1869, that when the main current of the river was directed into the pass, such activity would begin within 20 to 30 years, as has now happened.

CONTRIBUTION TO THE GEOLOGY OF EASTERN OREGON

BY E. L. ICKES[2]

(*Abstract*)

A statement of the general stratigraphy and structural features of eastern Oregon, with a more detailed discussion of certain formations and structures specially studied during a recent field trip in the east central part of the State.

CALIFORNIA EARTHQUAKES—A SYNTHETIC STUDY OF THE RECORDED SHOCKS

BY H. O. WOOD[3]

(*Abstract*)

A correlation of recorded shocks with the known faults of the region, and especially with those suspected to show recent activity.

SECONDARY PSEUDOSTRATIFICATION IN SANTA BARBARA COUNTY, CALIFORNIA

BY GEORGE D. LOUDERBACK

(*Abstract*)

There has developed in Tertiary friable massive sands an appearance of beds and of stratification planes, caused by secondary agencies acting at or near the surface. The appearance was described and illustrated and probable causes discussed.

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[2] Introduced by George D. Louderback.
[3] Introduced by George D. Louderback.

The paper was illustrated by specimens and lantern slides. Discussion by A. C. Lawson, H. F. Bain, and others.

AGE OF THE RANCHO LA BREA BEDS NEAR LOS ANGELES

BY JOHN C. MERRIAM

The paper was illustrated by lantern slides.

The section then adjourned for the day.

Session of Saturday, March 26

The meeting was called to order at 9.20 a. m., in room 22, South Hall, and proceeded immediately to the reading of papers presented as follows:

SUPPLEMENTARY NOTE ON THE ORGANIZATION OF THE GEOLOGICAL SOCIETY

BY C. H. HITCHCOCK

Published as pages 741-746 of this volume.

RECENT FAULTING IN OWENS VALLEY, CALIFORNIA

BY WILLARD D. JOHNSON[4]

(Abstract)

The topography of Owens Valley is strikingly immature. It is complex with arrested works of gradation. Deformation has varied as to the type and the magnitude of its results, the seat of its action, and the periods of its recurrence and gradation, continually modeling toward symmetry again, has made record of the diastrophic events.

This paper was illustrated by lantern slides and gave rise to many questions and general discussion.

PARAGENESIS OF MINERALS

BY AUSTIN F. ROGERS[5]

(Abstract)

Emphasized the interest and importance of the occurrence, association, and origin of minerals. Discussed the use of the term paragenesis. A university course along this line, in which paragenetic varieties of minerals are listed, correlates the facts of mineralogy and petrography and serves as an introduction to the study of ore deposits.

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[4] Introduced by George D. Louderback.
[5] Introduced by J. C. Branner.

RUBY CORUNDUM FROM SAN BERNARDINO COUNTY, CALIFORNIA

BY GEORGE D. LOUDERBACK AND W. C. BLASDALE

(*Abstract*)

A hitherto undescribed locality recently called to the writer's attention shows the occurrence of corundum as an igneous secretion followed by a history of partial metamorphism, impregnation, brecciation, and weathering of the inclosing rocks. The mineral is in part automorphic, with very simple forms. The rock and its associations are described and analyses presented.

The paper was illustrated by specimens.

SOME TOPOGRAPHICAL FEATURES OF THE WESTERN SIDE OF THE COLORADO DESERT

BY H. W. FAIRBANKS

(*Abstract*)

The San Jacinto Mountains send out a long spur southeastwardly into the western part of the Colorado Desert. This spur is known as the Santa Rosa Mountain. The accumulations of the desert appear to have been built up against the foot of this range as though it had undergone subsidence.

An arm of the Colorado Desert reaches in behind the Santa Rosa Mountain, and this is known as the Borego Desert. At the western end of this desert, close under the steep scarp of the Peninsula range, there is an alkali sink evidently due to subsidence of the desert.

At the end of the Santa Rosa Mountain, where the Borego Desert opens out into the main Colorado Desert, there are extensive beds of late Tertiary age. These have been folded slightly, and subsequently planed off. Then an uplift took place and another partial planation occurred. Finally the beds were dissected, and at their lower exposed margin eaten into by the waves of the ancient Salton Sea.

SERPENTINES OF THE CENTRAL COAST RANGES OF CALIFORNIA

BY H. E. KRAMM[6]

(*Abstract*)

The paper presented a brief history of the work done on the California serpentines. In particular it was a mineralogical and petrological description of serpentines and associated minerals in the central coast ranges of the State. The derivation of the serpentines from eruptive rocks was shown.

The following papers were read by title:

A NEW EROSION CYCLE IN THE GRAND CANYON DISTRICT, ARIZONA

BY H. H. ROBINSON

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[6] Introduced by J. C. Branner.

CONDITIONS OF FOSSILIZATION

GEOLOGY OF THE SANTA LUCIA RANGE, IN THE BIG SUR REGION

BY J. CULVER HARTZELL

The Secretary called attention to the fact that Mr. G. K. Gilbert, who had been elected a member of the section's Executive Committee, had changed his residence from the Cordilleran region and was therefore not eligible to a section office. The section then elected H. Foster Bain as Councilor.

REPRESENTATION ON THE COUNCIL

Professor Eakle brought up the matter of representation of the Cordilleran Section in the Council of the general Society. It was pointed out that the Cordilleran Section had had a successful existence for ten years, and that on account of the distance of its members from the places of meeting of the general Society and its consequent isolation, it had had very little opportunity for taking any direct part in the councils of the general Society. It was voted unanimously that the section petition the Society that it be given a representative on the Council.

RESOLUTION CONCERNING SEISMOLOGY

Professor Lawson brought up the matter of the present condition of seismology in America and the proposed establishment by Congress of a National Bureau of Seismology. After a general discussion, it was voted that the Secretary be instructed to prepare and forward to the President and officers of Congress and the congressional committees now considering the matter a set of resolutions embodying the unanimous opinion of the section favoring the establishment of such a bureau. The resolutions follow.

Resolved, That the Cordilleran Section of the Geological Society of America favors strongly the establishment of a National Bureau of Seismology organized under the Smithsonian Institution, with power

(*a*) To collect seismological data.

(*b*) To establish observing stations.

(*c*) To study and investigate special earthquake regions within the national domain.

(*d*) To cooperate with other scientific bodies and organizations and individual scientists in forwarding the development and dissemination of seismological knowledge.

It regards it of great importance that other scientific bureaus of the National Government, in particular the United States Weather Bureau and the United

States Geological Survey, be authorized by law to cooperate with this bureau in forwarding the purposes for which it may be established.

Resolved, That copies of this resolution be transmitted to the President, the President of the Senate, the Speaker of the House of Representatives, and to members of the congressional committees now considering this matter.

The section adjourned at noon *sine die.*

REGISTER OF THE BERKELEY MEETING

Fellows:

F. M. ANDERSON.
H. FOSTER BAIN.
J. C. BRANNER.
A. S. EAKLE.
H. W. FAIRBANKS.
E. W. HILGARD.
A. C. LAWSON.
G. D. LOUDERBACK.
R. H. LOUGHRIDGE.
J. C. MERRIAM.

Visitors and other geologists taking part in the meeting:

B. CLARK.
E. L. FURLONG.
G. C. GESTER.
W. R. HAMILTON.
J. KEEP.
H. E. KRAMM.
J. C. HARTZELL.
G. MCLAUGHLIN.
R. W. PACK.
A. F. ROGERS.
J. R. PEMBERTON.
G. McM. ROSS.
J. P. SMITH.
G. A. WILCOX.
H. O. WOOD.

There were also a number of students and other visitors.

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