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D, Petrography and Mineralogy, 29

DEPARTMENT OF THE INTERIOR

UNITED STATES GEOLOGICAL SURVEY

CHARLES D. WALCOTT, Director

PETROGRAPHY AND GEOLOGY

OF THE

IGNEOUS ROCKS

OF THE

HIGHWOOD MOUNTAINS, MONTANA

BY

LOUIS VALENTINE PIRSSON

WASHINGTON
GOVERNMENT PRINTING OFFICE
1905

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ILLUSTRATIONS.

LETTER OF TRANSMITTAL.

DEPARTMENT OF THE INTERIOR,
UNITED STATES GEOLOGICAL SURVEY,
Washington, D. C., May 11, 1904.

SIR: I have the honor to transmit herewith a manuscript entitled "Petrography and Geology of the Igneous Rocks of the Highwood Mountains, Montana," by L. V. Pirsson, and to recommend its publication as a bulletin of the Geological Survey.

This paper is a valuable discussion of one of the interesting centers of igneous rocks in a province already celebrated through the work of the author in conjunction with Mr. W. H. Weed.

Very respectfully,

C. W. HAYES,
Geologist in Charge of Geology.

Hon. CHARLES D. WALCOTT,
Director United States Geological Survey.

PETROGRAPHY AND GEOLOGY OF THE IGNEOUS ROCKS OF THE HIGHWOOD MOUNTAINS, MONTANA.

By L. V. Pirsson.

INTRODUCTION.

In the following work will be found the results of field and laboratory studies of the igneous rocks of the Highwood Mountains of Montana. The field work was carried out by Mr. Walter H. Weed and the writer, chiefly during the latter part of the summer of 1894, though the eastern part of the area was again revisited for a few days in 1896. The north-central part of the area, around the Shonkin and Arnoux stocks, was not visited by the writer, as this part of the work was done by Mr. Weed after the writer was called from the field. As the field work in petrology was incidental to the areal mapping of the region on the base map of 4 miles to the inch for the Fort Benton folio of the United States Geological Survey, under charge of Mr. Weed, the time that could be devoted to a careful study of details was necessarily limited. Future studies of the district may therefore bring out minor features which were not seen or which are but briefly treated.

As the result of this work during recent years a number of papers dealing with features of especial interest in the area have been published by Mr. Weed and the writer, including a summary account of the geology of the district by Mr. Weed in the Fort Benton folio. A list of these papers will be found in the bibliography (p. 15). It was also our intention to prepare a complete memoir on the geology and petrography of the region, but pressure of work in other and more important directions prevented this, and finally the writer was intrusted with the task of preparing a report on the geology and petrography of the igneous rocks. Since, however, the Highwoods are a group of eroded volcanoes, rising through almost undisturbed Cretaceous strata, the main problems of geologic interest connected with them are necessarily of a petrologic character and are therefore treated in this report. In carrying out the work the writer is under great obligation to Mr. Weed, who has freely tendered not only the material collected but also his field notes, maps, and photographs, and who has made many valuabe suggestions concerning the geology. The value of the work is therefore in large measure due to him.

Thanks are also due to Dr. H. S. Washington, who kindly allowed the writer to use, in advance of publication, the results of his collected tables of analyses, which proved of service in comparing a number of the types described with those of other regions.

CHAPTER I.

GEOGRAPHY AND HISTORY.

LOCATION.

The mountain group whose igneous rocks are described in this bulletin is one of the series of detached isolated areas which lie scattered about on the great plains of central Montana. Far to the west rises the great and continuous wall of the main chain of the Rocky Mountains, while to the east for a long distance stretches the level plains country. To the traveler going westward by the Great Northern Railway, these mountain clusters, rising in the distance blue and cloud-like from the level plain like islands from the sea, are the first mountain elevations seen after crossing the great basin of the

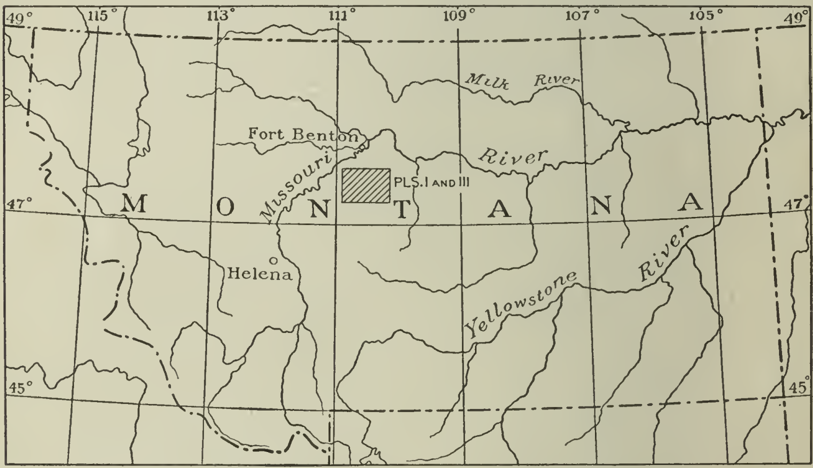
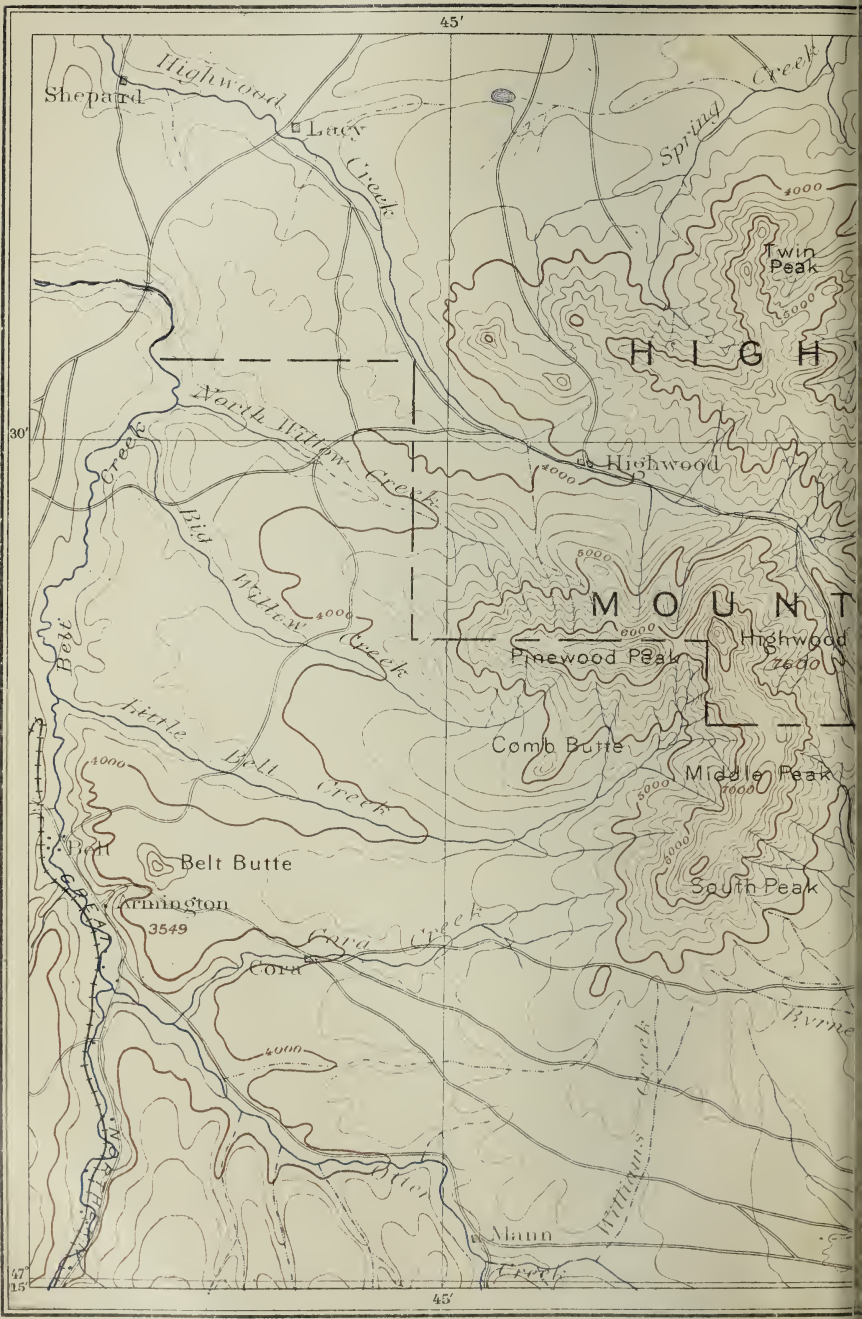


FIG. 1.—Index map showing location of Highwood Mountains.

Mississippi-Missouri system. The Highwood Mountains lie within the great bend made by the Missouri River as it flows across the plain after it issues from the eastern ranges of the Rocky Mountain system. They are definitely located by the meridian of 110° 30′ west longitude and the parallel of 47° 30′ north latitude, which intersect in the center of the group. The nearest mountain ranges are the Little Belt Mountains, about 20 miles to the south, the Bearpaw Mountains, about 50 miles to the northeast, and the Judith Mountains, about 50 miles to the southeast.

The area is reached on the north and east from Fort Benton on the Great Northern Railway, about 20 miles from the foothills. The stage route from Fort Benton to Lewistown passes by the eastern side

U. S. GEOLOGICAL SURVEY



Henry Gannett, Chief Geographer
A.H.Thompson, Geographer in charge
Triangulation by E.M.Douglas
Topography by Northern Transcontinental Survey
Surveyed in 1883-7

TOPOGRAPHIC MAP OF THE

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ḷHWOOD MOUNTAINS, MONTANA

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of the area, and there are relay stations and post-offices at Steele, about 4 miles east of Mallard Lake, and at Campbells, east of Square Butte. On the south and west the region is reached from Belt and Armington, towns on the Little Belt branch of the Great Northern Railway.

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12. Geology of the Shonkin Sag and Palisade Butte Laccoliths in the Highwood Mountains of Montana, by W. H. Weed and L. V. Pirsson: American Journal of Science, 4th series, vol. 11, 1901, p. 1.

TOPOGRAPHY AND GEOGRAPHY.

The elevated tract comprised in the Highwood Mountains in its greatest extension is about 25 miles long from east to west and 16 miles wide from north to south, and has a total area of 250 to 300 square miles. The outer foothills are rather low and rounded, with few craggy or broken tops. Toward the center the country becomes more rugged and the highest elevations are sharp peaks which rise 3,000 to 4,000 feet above the plains country and 6,500 or 7,500 feet above the sea. On the south side the descent to the plain is much more abrupt than on the north. The two highest mountains, Highwood Peak (7,600 feet) and Arrow Peak (7,420 feet), are separated by a deep pass known as Highwood Gap, which, with the valleys descending from it, divides the mountains into two portions. One of the main roads across the mountains runs through this pass. A view of the mountains, looking north from near the divide in Highwood Gap, is given in Pl. II, *A*.

On the south the streams drain into Arrow Creek, which heads in Highwood Gap; on the west they are tributary to Belt Creek. The northern portion of the area is drained by the heads of Highwood and Shonkin creeks, which flow directly into the Missouri. Within the mountain tract the streams are bright running brooks of clear cold water, generally with abundance of trout and whitefish; but as they debouche upon the plain they are apt to become sluggish and alkaline from the Cretaceous clays, and in summer are sometimes dried away to standing pools. The upper stream valleys, cut in the rather soft Cretaceous beds or volcanic breccias, are of typical V form, with rather sharp descent. The general form of the drainage is radially outward from the mountain group and of branching pattern.

The slopes, except where broken by the projecting craggy walls of protruding dikes or sheets, are rather smoothly modeled, talus heapings and screes being somewhat uncommon, and are usually carpeted with a thick growth of grass. The upper northern slopes, however, are covered by heavy forests of small pines and often by dense thickets of the lodgepole pine (*Pinus murrayana*). There is no doubt that these thick blankets of pine on the northern slopes caused the mountains to receive the name "Highwoods."

The outer foothills, and especially the openings of the valleys upon the plains, are generally utilized as ranches, and the available water is used for irrigation. The higher slopes and the semiarid stretches of plains country are given up to pasturage.

All parts of the area are very accessible, as roads run up all the valleys and in one or two places cross the higher ridges. The generally smoothly modulated mountain slopes are easily traversed on horseback.

The temperature shows the same range that generally characterizes Montana, although extremes of heat and cold are greatly moderated by the dryness and vigor of the atmosphere. As the mountains stand isolated upon the plain they are condensers of moisture, and in summer time are frequently the focus of local thunder storms that help to keep green the vegetation of the higher slopes.

HISTORY.

So far as known to the writer, the Highwood Mountains are first mentioned in the reports of the Lewis and Clark expedition,[a] though they are not given a definite name. They are mentioned several times

[a] Coues's History of Lewis and Clark Expedition, vol. 1, p. 342.

A. VIEW NORTHWARD FROM HIGHWOOD GAP, SHOWING SLOPES OF VOLCANIC DEBRIS.

B. UPPER DAVIS CREEK; MOUNTAINS OF VOLCANIC FLOWS AND BRECCIAS.

by Governor Stevens in his report,[a] and it is evident from his narrative that nearly all the mountain groups and streams of this region had then, in 1853, received the names they now bear. The Belt Mountains are called by him, however, "Girdle" Mountains, and a variant of Shonkin is Shonkee Creek, which is probably a misprint. The pine timber on the Highwoods and its probable usefulness to the surrounding region in the future is commented upon by him. Lieutenant Mullan of the Stevens expedition,[b] with a detached party, ascended Shonkin Creek and passed to the east of the Highwoods into the Judith basin. He speaks of the first spurs of the Highwoods as being a thousand feet in height.

In 1860 Lieut. John Mullins[c] passed along the same route on his way from Fort Benton to Fort Union. His first camp was in the foothills on the northeast side of the mountains, and the next day he followed the Shonkin Sag down to Arrow Creek. On the map accompanying the report the position of the mountains is roughly indicated, but their name is not given. The mountains were not visited by the Ludlow expedition in 1875,[d] but on the route map their position is shown and their name is given, together with those of the prominent peaks and the main streams.

The earliest mention of the geology of the Highwoods is by Prof. F. V. Hayden.[e] In a summary of the geologic results of Raynold's expedition, which he had accompanied, he says:

In the Belt, Highwood Mountains, and indeed all along the eastern slope in this region we find continual evidence of the outpouring of the fluid material in the form of surface beds or in layers thrust between the fossiliferous strata. These igneous beds thin out rapidly as we recede from the point of effusion. A large number of these centers of protrusion may be seen along the slope of the mountains west of the Judith Range. The erupted material sometimes presents a vertical wall 300 feet high, then suddenly thins out and disappears.

Almost the same wording is used in his report accompanying that of Warren's explorations.[f] This statement applies very well to the laccoliths of the region. From Raynold's[g] report we know that Mullins, whom Hayden accompanied, passed down the valley of what is now called the Shonkin Sag to Arrow Creek, and thus passed the cliff wall of the Shonkin Sag laccolith. He probably had this in mind when writing the above, and also in his report on the geology of the country traversed by the expedition, which appeared about ten years later. In this he says:

From Fort Benton we crossed the prairie country in an easterly direction not far from the foot of the mountains. We find the cretaceous beds predominate,

[a] Explorations and Surveys for a Railroad Route to the Pacific, vol. 12, pp. 123, 173, 239.
[b] Ibid., p. 123.
[c] Raynolds, W. F., Exploration of Yellowstone and Missouri Rivers in 1859-60, 1868, p. 93.
[d] Ludlow, W., Reconnaissance from Carroll, Mont., to the Yellowstone Park, 1876, p. 14.
[e] Am. Jour. Sci., 2d series, vol. 31, 1861, p. 233.
[f] On the Geology and Natural History of the Upper Missouri, 1862, p. 119.
[g] Op. cit., p. 163.

with here and there indications of eruptive rocks, and we know that the mountains that surround us on every side are very largely composed of that material. The country is covered with saline lakes, which add much to the desolateness of the scenery. We have near the Arrow Creek a bed of erupted material thrust between cretaceous rocks, which presents a vertical wall of 150 to 200 feet at one point and then suddenly ceases. These small centers of effusion of melted rock seem to cover this whole region. The most conspicuous examples of ejected material are the Square Buttes, which is a general name for numerous peaks with broad, flat upper surfaces and with a tendency to a lofty, square, columnar form. The cretaceous rocks, so far as I can see, seem to extend quite closely up to the mountain elevations, and everywhere present the lithological character of No. 2. Arrow Creek is a small stream with a narrow fringe of cottonwood, surrounded with high bluffs forming very rugged features, properly called Bad Lands. On Arrow Creek I found ammonites, cardium, baculites, inoceramus, etc. The cretaceous rocks in this region seem to belong entirely to No. 2, though Nos. 1 and 3 may be included. It is mostly a black plastic clay, with now and then a bed of sandstone. The igneous rocks in this region show very distinctly the origin of the vast quantities of saline matter which covers the ground and mingles with the waters of the streams. These rocks seem to contain large quantities of this saline material, which gathers upon their surface, giving to the igneous peaks a whitish appearance. This may account for the great quantities of it which pervade the formations in the West.

Beyond the few observations of these early explorers, the first geologic examination of the district was made by W. M. Davis and W. Lindgren, at that time attached to the Northern Transcontinental Survey, in 1883. They traversed the mountains through Highwood Gap, collected material, and the results of their reconnaissance, showing the essential geologic features of the mountains, have been published.[a] In this report Lindgren gives a brief résumé of the petrography of the igneous rocks, showing what interesting types the region affords. This sketch of the petrography of the area will be alluded to more in detail later on. Lindgren continued his petrographic studies of Highwood material, and in 1890 published a paper on the analcite-basalts,[b] which was followed in 1893 by an article on the syenite of Square Butte,[c] with included chemical analyses by the late Dr. W. H. Melville, this last paper being based on material collected by Dr. C. A. White.

In 1894 the area was explored and mapped by W. H. Weed and the writer for the purpose of studying the areal geology and mapping the Fort Benton quadrangle for the United States Geological Survey, the work being in charge of Mr. Weed.

The writer was not able to complete the field season on account of other duties, and hence a portion of the area around the head of Shonkin Creek and the Shonkin stock was not seen by him, the work being completed by Mr. Weed, and the material collected by him. In 1896 a brief visit was made by Mr. Weed and the writer to the

[a] Tenth Census, vol. 15, p. 709.
[b] Proc. California Acad. Sci., ser. 2, vol. 3, 1890, p. 51.
[c] Am. Jour. Sci., 3d ser., vol. 45, 1893, p. 286.

laccolithic area on the eastern side of the mountains, at which time the Shonkin Sag laccolith was studied.

As results of this field work and collection of material a preliminary sketch of the geology of the mountains, accompanied by a detailed study of the petrology of Square Butte, was published by Mr. Weed and the writer in 1896,[a] and this was followed by two papers, one dealing with the description of missourite,[b] a new type of leucite rock occurring in the Shonkin stock, the other with the geology of the Shonkin Sag and Palisade Butte laccoliths.[c]

The results of the areal work and mapping have been presented in the Fort Benton folio of the Geologic Atlas of the United States, with descriptive text by Mr. Weed.

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[a] Bull. Geol. Soc. America, vol. 6, 1895, p. 389.
[b] Am. Jour. Sci., 4th ser., vol. 2, 1896, p. 315.
[c] Ibid., vol. 11, 1901, p. 1.

CHAPTER II.

GEOLOGY OF THE IGNEOUS STOCKS.

INTRODUCTORY.

Briefly stated, the general geology of the Highwood Mountains is that of a group of extinct and greatly eroded volcanoes. Beyond this the details are largely of local and in only a few particulars of general interest. On the southeast of the mountains, and scarcely separated from them, is a restricted area of intruded sheets and laccoliths. In the eroded volcanic area proper occur all the concomitants of violent extrusive volcanism. There are central cores or stocks representing the main canals to large bodies of magma below; there are great masses of piled-up breccias mingled with lava flows, which are, however, only remnants of former lofty cones; finally, there are networks or systems of dikes surrounding and dependent upon the central cores, cutting sediments and breccias alike, and generally showing a remarkable radial arrangement around the centers of eruption to which they belong.

Brief accounts of the general geology of the Highwoods have bee. already given by Mr. W. H. Weed and the writer,[a] and in somewh more extended form by Mr. Weed.[b] It is intended here to describ only such salient features as are necessary to an understanding of th petrology of the area, the main purpose of this bulletin. In essenti points the descriptions here given are similar to those in the work just cited, though presented in more extended form. The geologi map (Pl. III) is taken from the map given in the Fort Benton folio.

HIGHWOOD PEAK STOCK.

The highest peak in the mountains marks the location of an approximately circular body of granular igneous rock about a mile in diameter. The igneous mass is in contact in places with Cretaceous sandstones and shales which are disturbed and metamorphosed and in places with breccias which have been indurated by it. It consists of two very distinct and separate types of rock, one a syenite of Albany type (pulaskose in the new classification), the other a monzonite (sho shonose). As one is so feldspathic and devoid of dark minerals tha

[a] Bull. Geol. Soc. America, vol. 6, 1894, p. 389.
[b] Description of the Fort B ton quadrangle, Geologic Atlas U. S., folio 81

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LEGEND

SURFICIAL ROCKS

Pbg — Bench gravels

Pgd — Glacial drift and till

SEDIMENTARY ROCKS

Km — Montana formation
(clay-shale with sandstone interbedded and at the top)

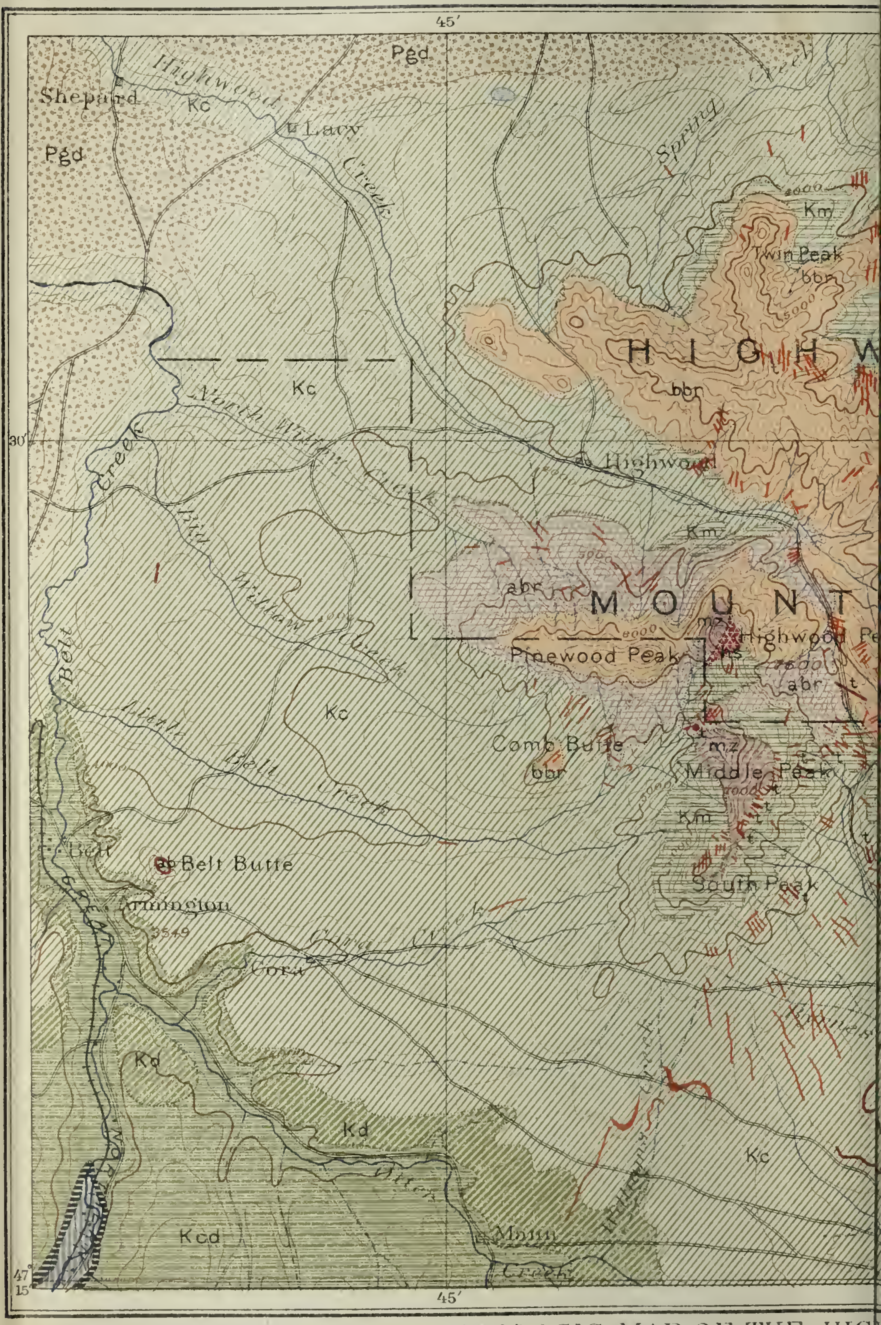
Ke — Eagle formation
(white sandstone with lignite seams and clay)

Kc, ab — Colorado formation
(black shale at the base gray shale above, and sandstone interbedded; contains an ash bed, ab*)*

Kd — Dakota formation
(sandstone and inter-bedded clay shale)

Kcd — Cascade formation
(sandstone and shale with coal seam at the top)

Je — Ellis formation
(limestone grading upward into sandstone and pebbly sandstone at the base)



Henry Gannett, Chief Geographer
A. H. Thompson, Geographer in charge
Triangulation by E. M. Douglas
Topography by Northern Transcontinental Survey
Surveyed in 1883-7

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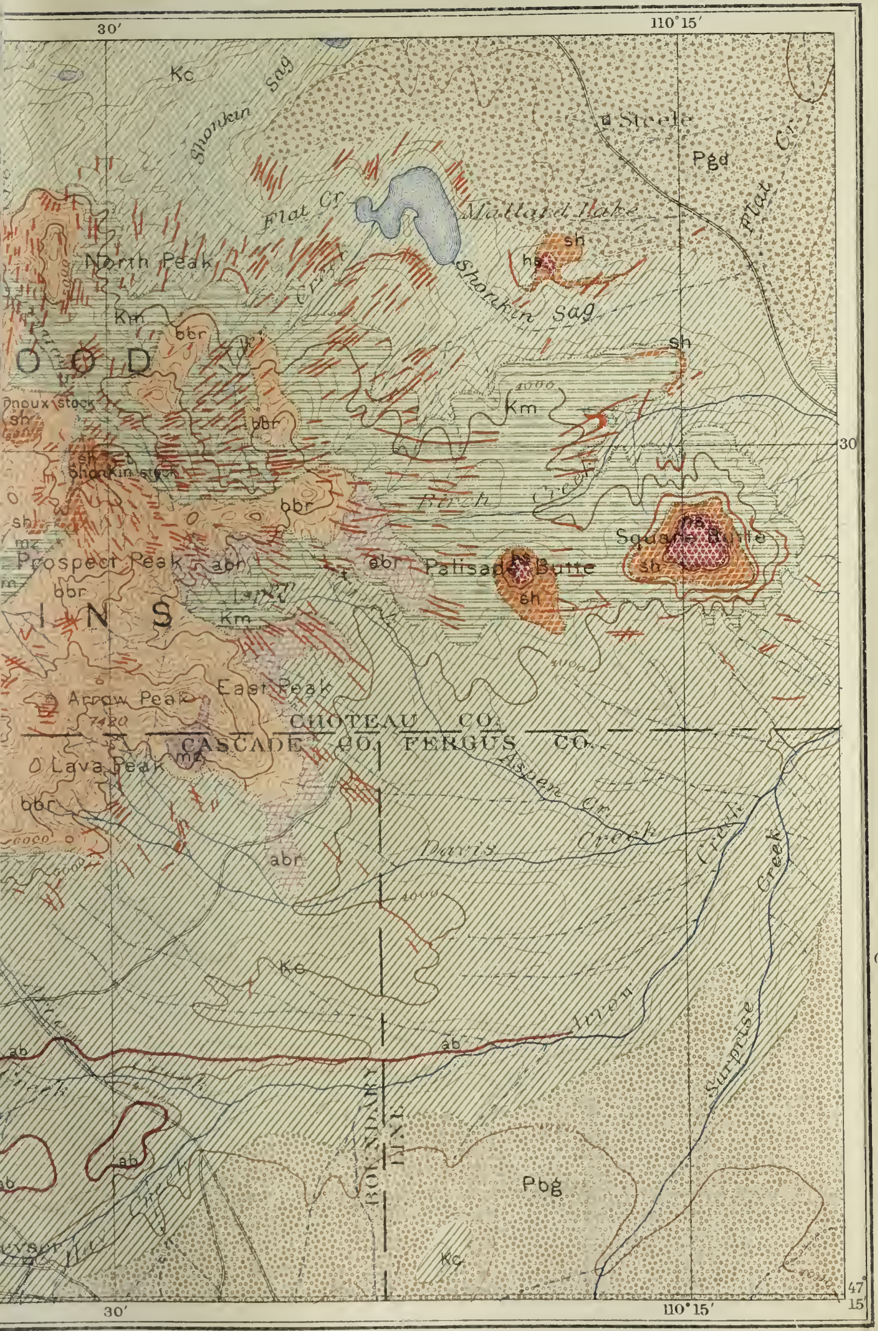

WOOD MOUNTAINS, MONTANA

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Geology by Walter Harvey Weed and Louis V. Pirsson
Surveyed in 1894

LEGEND
(continued)

Cq — Quadrant formation *(sandstone, green and red shale, and white limestone)*

IGNEOUS ROCKS

hs — Syenite *(in part sodalite-syenite)*

mz — Monzonite *(also basic syenite of Middle Peak and leucite-shonkinite of East Peak)*

sh — Shonkinite *(including missourite and fergusite of Arnoux stock)*

Basaltic sheets and dikes *(Highwood minette, analcite and leucite-basalts)*

bbr — Basaltic breccia, flows, and scoria *(analcite-and leucite-basalts)*

t — Trachytic dikes and sheets *(syenite-and tinguaite-porphyries)*

abr — Trachyandesitic breccia and tuffs

it appears almost white in considerable masses and the other is very dark, the contrast between them is pronounced. On the southern portion of the peak the syenite forms the exposed crags, and outcrops on the slopes and in the heads of the valleys. Masses of upturned and altered Cretaceous beds are seen lying against it, but they are not large and, so far as can be told, its intrusion was not followed by any extensive or important displacement or rupturing of the sediments. The coarsest-grained rock, of a somewhat miarolitic type, is found in the highest masses exposed, but nearly everywhere the rock is moderately coarse.

Along the divide running to Middle and South peaks are occasional outcrops of massive rock above the smooth slopes of gray indurated ash. It appears probable that they represent apophysal tongues of somewhat differentiated character, which extend in this direction perhaps as irregular dike-like masses, and, as they occur at irregular intervals, may possibly extend to and connect with the Middle Peak mass.

On the summit of Highwood Peak the light-colored rock soon gives way on the north to dark-colored monzonite. The contact between the two was not observed in place on the summit, but among the slide-rock débris of the west slope are found not infrequently pieces showing the two types in contact. In these the white syenite holds small angular chips and fragments of the monzonite, torn and displaced from a wall of the dark rock, and it is inferred that the syenite was intruded later than the monzonite.

At the north end of the peak the monzonite becomes very dense and trap like, and it is supposed that the contact is close by in this direction. The peak is sharp on all sides, and the exposures of the crest give way rapidly to a rolling talus of small fragments, which in turn is succeeded by the smoothly modeled grassy contours of the lower parts. In such places the structure is not exposed, but can only be inferred from the crest above.

Taking into consideration the rudely circular form of the mass, the grain of the rock, the small amount of displacement of the inclosing strata, the numerous radiating dikes, and the surrounding breccias and flows of lava, it appears almost certain that the core of igneous granular rock forming Highwood Peak represents the plugged canal of a former volcano. This core of igneous rock was once of much greater height and size, and the column of liquid lava rose through the conduit of sedimentary rocks into a cone of mingled ashes and breccias. The size of this cone can not now be accurately determined, but it was certainly considerable as compared with the present size of the mountain mass, as is indicated by the portion still remaining west of Highwood Peak and forming the high, narrow ridge called Pinewood Peak. This consists of dark-colored, basic breccias overlying lighter, more acidic ones, indicating variations in the character of the material erupted at different periods.

Since the cessation of igneous activity a large amount of erosion has occurred, removing the overlying breccias and flows in great part, leaving masses of them here and there and in other places cutting into the sediments, so that now the core is well exposed, and being the central and most resistant rock mass of the complex, it now forms the highest peak.

CHARACTER OF THE BORDER CONTACT OF HIGHWOOD PEAK STOCK.

On the southwest slope of Highwood Peak the character of the contact at the periphery of the mass is such that it deserves especial mention. Here outcrops of igneous rock run tongue-like down the mountain slope, with strips of inclined, much altered, sediments between them. The main rock is the syenite of the crest, mentioned above, but it contains some mica in addition to the augite. It is here cut by or is in contact with stringers and masses of a kind of "mica trap"—a dark ferromagnesian rock—at times containing much biotite in a dark-gray groundmass. This phase passes quickly, in many of these stringers and masses, into a leucite facies. The change may take place within a few inches, often in the distance of an inch. The large biotite phenocrysts disappear, the mica flakes become much smaller and more intimately mixed in the groundmass, and spots of leucite-like character appear until the rock closely resembles well-known varieties of leucite-basalt. A remarkable feature is that when the actual contacts of the light and dark rocks are examined it is found that the light incloses angular fragments of the dark, while, vice versa, the dark incloses the light. This occurs in a large number of cases, so that it is a common and persistent feature of the contact. It is also noticed, especially on somewhat weathered surfaces, that the white syenite appears somewhat streaked and eutaxitic. Observation does not reveal any change in granularity by which it may be told whether the light or the dark is the older.

Movements may have taken place in the conduit among masses of magma already differentiated, as at Square Butte, and in a highly viscous condition, or the dark rock may have been ejected through the light one and carried fragments of it upward, while the light rock held pieces of a previously solidified basic magma. The latter would seem on the face of it the more reasonable supposition, since around the peak are basaltic lavas resting on feldspathic ones. The order of succession of the igneous rocks is discussed in Chapter VII.

As one follows around the slope to the west the dark rock is seen to replace the white entirely, and the projecting masses and crags among the upturned sediments may be the roots of former effusions breaking through the side of the cone. This idea is supported by the fact that as the saddle east of Pinewood Peak is approached the rock becomes less and less granular and denser, assumes in places an amygdaloidal structure, and finally on the saddle and on Pinewood Peak has the character of a true effusive and is even strongly pumiceous.

MIDDLE PEAK STOCK.

As previously mentioned, small intrusive masses frequently break through the level-bedded sandstones or indurated beds of ash which mostly compose the high ridge connecting Highwood Peak with Middle Peak and extending to South Peak. These are of granular rock ranging from extremely feldspathic syenites to dark basic types composed chiefly of augite and other ferromagnesian minerals. These small intrusives and also the dikes along the ridges indicate connections with deeper-seated masses below. At Middle Peak, however, is a large body or stock of granular igneous rock. The intrusion, as seen on the map, is of roughly circular outline. Its eastern edge follows the crest of the ridge along the contact with the Cretaceous sandstones, and its western boundary is on the western slope, where its presence is shown by crags outcropping among the slide-rock débris. To the south the intrusion is continued in a long tongue-like apophysis of no great breadth which runs south for 2 miles or more on the eastern side of the ridge a little below the crest. The thickness or breadth of the apophysis is, however, somewhat variable and is difficult to make out, as the lower edge is so commonly masked by débris; its outcrops are well seen on some of the spurs extending east from South Peak.

The rock composing this intrusion varies somewhat in fineness of grain and relative amount of feldspathic and ferromagnesian minerals, but in general is of medium nature. It is dark gray, moderately even granular, resembles many diorites, and in the hand specimen is extremely like the monzonite of Highwood Peak, though, as shown later in the petrographic description, there are several important points of difference. At the contact the feldspars are apt to be of pronounced tabular habit and arranged in parallel fluidal structure. In the apophysis to the south a varietal phase replaces the type of the main mass, biotite becoming a prominent ingredient. Owing to its close resemblance in the common variety to the monzonite of Highwood Peak, it has been given the same color and pattern on the map.

CONTACT PHENOMENA OF MIDDLE PEAK STOCK.

Along the crest of the Middle Peak–South Peak ridge the contact between the stock and the sedimentaries is clearly and beautifully shown. In fact, at this point the hard, tough, and resistant altered beds appear to determine the crest of the ridge, since they resist erosion better than the granular igneous rock on the one hand

and the softer unaltered shales and sandstones on the other. The igneous rock itself does not appear to be modified at the contact. The full size of grain continues directly to the contact wall, which is irregular, the igneous rock penetrating the sediments in stringers, bulbous masses, and veins for a short distance, producing a narrow mixed zone. The sediments at such places, on the contrary, are greatly altered, and where they contained lime-bearing material a greenish pyroxenic rock is produced carrying garnets and chlorite. Where they were clay slates a dark, tough, dense hornstone or adinole is produced, similar to that observed at Castle Mountain[a] and in the Crazy Mountains.[b] Changes into spotted slates, audalusite, or mica hornfels were not observed, as described by various writers at other localities.

The width of the adinole zone is probably about a quarter of a mile, not greater. The metamorphic effect dies away at South Peak, although on the crest it is still strongly marked, and while the lines of bedding are not wholly obliterated, they are twisted and gnarled, and original lime-bearing nodules are converted into hard concretionary masses, often hollow and lined with pyroxene crystals. These rocks weather purple, gray, and green on the surface. Where the metamorphism is most marked the pure sandstones have been changed into hard quartzite. The beds show great shrinkage, and in places on the ridge where they are exposed to a thickness of 15 feet they have split into prisms often several feet in diameter. They roughly resemble basaltic columns and form large blocks in the sharp-edged and chippy talus. Such shrinkage and cracking of the sediments by metamorphism about an igneous core may have an influence in permitting the intrusion of dikes into them at a later period.

ENDOMORPHIC CONTACT PHENOMENA OF MIDDLE PEAK STOCK.

The igneous rock, as previously said, holds its full size of grain, as well as could be told, to the contact, but changes somewhat in texture. The feldspars become of a more distinct tabular habit and are arranged more or less roughly parallel to one another and to the contact, so that the rock splits more easily in this direction. The effect is somewhat similar to that seen in the well-known syenite from Plauen near Dresden, and is probably the result of fluidal movements in the crystallizing magma which tended to "set" or orient the developing feldspars.

EAST PEAK STOCK.

The piled-up masses of flows and breccias that form Arrow Peak are continued to the south and east by two mountain ridges, inclosing a

[a] Weed and Pirsson, Geology of the Castle Mountain mining district: Bull. U. S. Geol. Survey No. 139, 1896, p. 94.

[b] Wolff, J. E., Geology of the Crazy Mountains: Bull. Geol. Soc. America, vol. 3, 1892, p. 451.

basin in which are the headwater tributaries of Davis Creek. From the open country below, the view of this basin and its encircling mountain walls is very picturesque. The smoothly modeled slopes of the foothills are bare of vegetation save for the pale-brown nap of grass that covers them in summer time. In the stream bottoms is a luxuriant growth of cottonwoods and smaller trees—masses of vivid green against the brown. Above these rise the mountains, the dark-chocolate-brown of their rugged sides and crags softened here and there by forests of dark pines. The general effect, looking northward from Davis Creek at East Peak, is shown by Pl. II, *B*, from a photograph by Mr. Weed. At this point the flows and breccias composing the ridge are interrupted by a body of granular igneous rock approximately a mile in diameter and of the general shape shown on the map.

On the mountain slope this mass of igneous rock has been eroded into massive crags, pinnacles, and precipices that are noticeable at a considerable distance and from below are very striking. It ascends nearly to the top of the ridge, and on the northeast and west sides passes under the breccias which compose the ridge and which have been baked and altered by it. Its exposure slopes to the south and is terminated by a shallow, narrow valley running parallel to its face. The low ridge forming the south side of this drain also affords exposures of the massive rock in place in contact with tuffs and breccias. These latter on the slope to the south are soon replaced by the underlying Cretaceous sediments, on which it is clear they form only a shallow patch, and with which on the south side the igneous rock must be in contact at no great depth. From this exposure on the southern ridge was taken the specimen analyzed (760, p. 109).

A marked feature of this rock is the heavy massive jointing, which produces hugh angular blocks in the talus, which then weather and break down into smaller masses. The jointing causes the crags and pinnacles to have the form of great prisms or nearly rectangular masses. It gives in places a decidedly columnar aspect to the exposures. The columns are not vertical, but inclined in the same direction as the general slope of the exposed face of the mass. The breccias, beneath which the igneous rock disappears, are tilted away from it, as shown by their rough bedding lines, at angles of 10° to 20°.

All this goes to show that the stock or core in its general direction is not vertical, but dips somewhat to the north. It extended upward into previously piled-up masses of extrusive material. Whether it reached the surface and became in itself a conduit for effusions can not now be told. If effusive rocks existed at all, erosion has long since swept them away and has cut down into the stock itself and the surrounding breccias until on the southern edge they have almost disappeared.

The rock composing this stock is medium granular and pearly gray to dark gray in color. It contains so large a proportion of augite, chiefly with other ferromagnesian minerals mingled with its feldspars and feldspathoids, as to be of rather basic type. In the specimen analyzed, taken from the exposures of the low frontal ridge mentioned above, it contains among the feldspathic components a considerable quantity of leucite, and in the prevailing terminology would classed be as a basic leucite-syenite. It is described in the petrographic portion of this work under the name "leucite-shonkinose."

SHONKIN STOCK.

This locality was not visited by the writer, and for the following notes and the specimens which illustrate the variations in the rock mass he is indebted to Mr. Weed, who studied the occurrence after the writer had left the field.

The Shonkin stock is the largest body of intrusive granular rock in the mountain area, being about $2\frac{1}{2}$ miles long and $1\frac{1}{4}$ miles in its greatest breadth. It is irregular in shape, being broader at each end than in the middle. It is in places in contact with the sedimentary strata—Cretaceous shales—and in places with volcanic ejections which lie upon them. The igneous material has been intruded into the sediments and along the contact between the sediments and the extrusive volcanic material. All this material is greatly altered by the intrusion, and through the hardened rim there depart radially outward a great number of dikes. The igneous rock, whose average type is a rather coarse, dark, granitoid-looking rock, resembling many gabbros in appearance, from place to place shows great variation in grain and a slight difference in the relation of feldspathic and ferromagnesian minerals. This is most noticeable at the south end, where a coarse agglomerate of the massive rock in blocks has a cement of finer material, the mineral composition of both rock and cement being the same as that of the main type, but showing great textural variations. This is supposed to be the actual locus of volcanic activity—the throat, in fact, of the former volcano at this place. The mass is so eroded and weathered that it seldom forms heavy outcrops, acting in this respect like many coarse-grained stocks which readily break down. Conspicuous exposures may be seen near the contact, but the rock is apt to be hidden by the talus-like material which results from the breaking down of the mass. The jointing is platy at the contact, but massive elsewhere.

The rock composing this mass is made up mainly of dark ferromagnesian minerals—augite, olivine, biotite, and iron ore—but a considerable amount of a light-colored mineral is present. In some places the latter is alkali feldspar, forming shonkinite (shonkinose); in other places it is leucite, forming missourite (missourote), described on page 115. These two minerals, both white, formless and granular, look so much alike in the hand specimen that it is almost impossible to distinguish between them, and therefore between the two rock types, by mere inspection. Moreover, there are intermediate types in which alkali feldspar and leucite are intermingled in the white portion. As these facts were unknown when the area was mapped, and as the types could not be discriminated by ordinary means in any case, it is impossible to say how much of the Shonkin stock consists of missourite and how much of shonkinite. In the specimens collected by Mr. Weed over a large portion of the stock the shonkinite greatly predominates, and it is therefore inferred to be the chief type. At some places in the Highwoods where intrusions occur near the contact, the rock mass, which consists of shonkinite, is filled with large, coarse pseudoleucites, as large as the end of one's thumb, which contain many grains of ferromagnesian minerals. This fact renders it uncertain how much of the shonkinite in this area may be original and how much may be pseudoleucitic after missourite. This uncertainty also is all the greater when one takes into account the rock forming the neighboring Arnoux stock, whose white mineral, described on page 83, consists mainly of pseudoleucite.

Occurrence of missourite.—The pure unchanged leucite type (missourite) of this stock has been already described by the writer from Mr. Weed's specimens. The rock is of importance on account of the place it fills in the prevailing systems of classification, and because until this occurrence was known, unchanged leucite had never been found in an intrusive granular igneous rock, a fact of great importance in theoretic petrography. It was supposed that the whole mass of the Shonkin stock was made up of this type, but since subsequent study has shown that this is not the case, the exact locality where typical missourite occurs will be described. For the accompanying sketch map (fig. 2) the writer is indebted to Mr. Weed. The type specimen was taken from the talus blocks at the foot of a low cliff of a reddish color above the ranches on the east side of the stream, which is the head fork of Shonkin Creek. It will be noted that the place is at the southwest foot of the mountain between the main upper mountain forks of Shonkin Creek, and is on the border of the intruded masses of the stock. The leucite of the rock at this place is a pale greenish-gray on a freshly broken rock surface, while in those places where it is replaced by feldspar the latter is white to pale pink, if one can judge from Mr. Weed's specimens.

The adinole zone of contact-metamorphosed shales is largely filled with intrusive sheets of varying thickness. These sheets are composed of types of leucite-basalt—dense dark rocks spotted with phenocrysts of augite and whitish ones of pseudoleucite, similar to those types which occur in the sheets around Square Butte and the Shonkin Sag laccoliths and whose petrographic characters are described on page 166. The sheets and dikes are described on page 30. It should be remarked in conclusion that the edge of the stock is cut by dikes, one of which is a light-colored feldspathic porphyry (syenite-porphyry or trachiphyro-borolanose).

ARNOUX STOCK.

The Arnoux stock is a small, rudely circular mass of granular intrusive rock perhaps a mile in diameter. It is about 2 miles north-

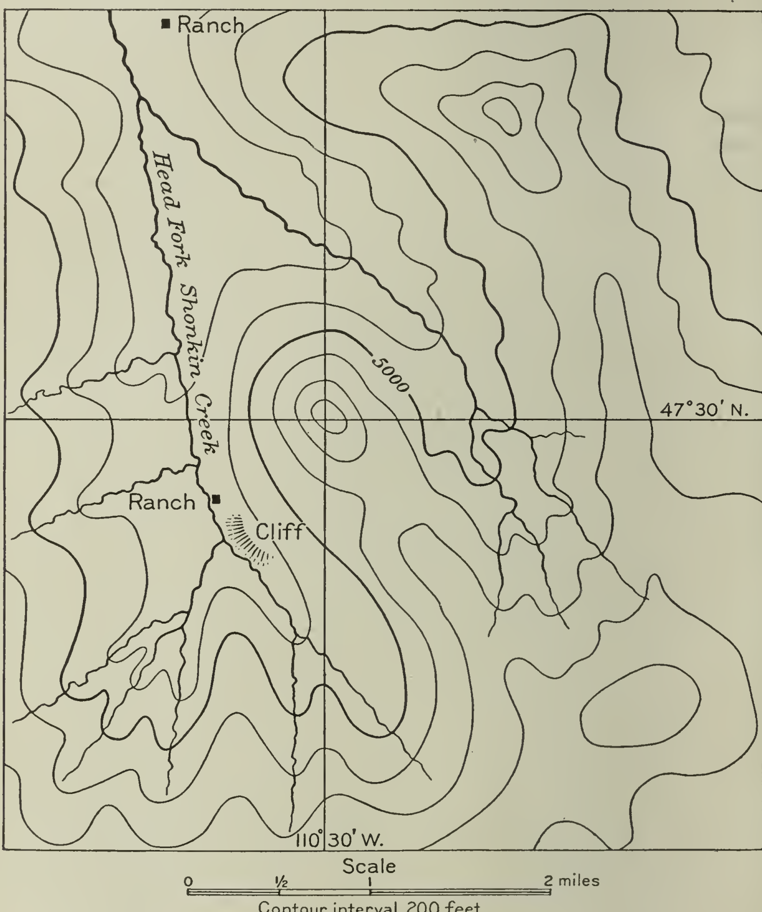

FIG. 2.—Sketch map showing locality at which missourite was found.

west of the large Shonkin stock. It is intrusive in the previously ejected basaltic breccias, which have been altered by it as at the Shonkin core. It has been cut into by a northward-draining tributary of Shonkin Creek, and although the exposures are not marked, they are good in places. While there is some variation in the rock composing it, the main type, as shown by Mr. Weed's specimens, has a very interesting composition and consists chiefly of pseudo-leucite and a smaller quantity of augite. The rock is fully described on page 83 under the name fergusose (fergusite), as it is a new and distinct variety of igneous rock.

At some places this rock contains a larger proportion of the ferromagnesian minerals, and at others, near the contact, the outline of the pseudoleucite may be lost, and the rock has then the appearance of the shonkinite of the other localities in the region.

This stock is entirely isolated at the surface, and as it was not visited by the writer he has no suggestions to offer concerning any possible connection with the near-by larger Shonkin stock, although this naturally presents itself as a possibility.

CHAPTER III.

GEOLOGY OF THE SHEETS, DIKES, AND EXTRUSIVE ROCKS.

INTRUSIVE SHEETS.

In the region of active volcanic outbreaks in the Highwood Mountains intruded sheets of igneous rocks do not form a prominent feature of the geologic structure. Only in the eastern laccolithic area are they important. They are not entirely wanting, however, for they have been noted in several localities—in the foothills or lowest slopes and in the open country surrounding the mountains where the trenching of the streams has revealed them, and in the altered strata surrounding the Shonkin stock. In the highest parts of the mountains they seem to be wanting among the sediments, except in one or two rather doubtful cases.

Near the Thornton ranch, on the head of the South Fork of Williams Creek, a sheet of minette of Highwood type (phyro biotitic shonkinose) is intruded into sandstones. It is about 12 feet in thickness, the upper portion being of coarser grain than the lower, has a brownish color, and weathers to a coarse sand. The lower, denser portion has a very massive parting, giving rise to large blocks which tend to weather to rounded bowlders. The sheet is full of large, well-developed mica phenocrysts, sometimes half an inch in diameter, which are more or less parallel to the general plane of the sheet and tend to cause parallel fracturing or lamination in its upper portion.

Several similar sheets were noted in the bench lands to the west of this occurrence. They commonly determine the position of the upper surface of the bench, forming, together with the baked sedimentaries, a hard layer in the soft Cretaceous strata. In one case the rock, on weathering, has developed a pronounced onion structure of concentric shells. The inner kernels may be lifted out, leaving bowls an inch or so in thickness and smooth and regular in appearance. In this instance the rock is badly weathered and the structure was evidently the result of concentric cooling, aided perhaps by a previous rolling and kneading of the viscous intrusion, which has been brought out by weathering. In other cases the sheet may have a thin platy parting at top and bottom, so that at a short distance it resembles a slaty sedimentary bed.

One of these sheets is cut by the long dikes crossing the bench lands north of Mann, on Otter Creek. In this area the beds at times show small local anticlinal dips, suggesting that they were disturbed below by intrusion of sheets or small, flat laccoliths, which erosion has not yet exposed at the surface.

The rock forming the sheets is the minette of Highwood type (phyro biotitic shonkinose). Sheets of feldspathic porphyry so common in the Little Belt Mountains to the south are seldom found in the Highwoods. These basic sheets break down into coarse soil and rotten rock, in which the micas turn to greenish plates of chlorite. An excellent example of this may be seen on the little hill in the open country south of the mountain slopes a few miles east of the Curry ranch, which is situated where Arrow Creek debouches from Highwood Gap.

Sheets of such rock in the black shales occur above Fitch's ranch, on Little Belt Creek, near its upper forks. They were also observed by Mr. Weed in the adinole zone around the Shonkin core at the head of Shonkin Creek, where they reached 8 feet in thickness. A heavy intrusive sheet found by Mr. Weed on the creek between Alder and Birch creeks, on the eastern side of the mountains, is about 20 feet in thickness and produces a waterfall in the course of the stream; a 5-foot dike runs into it and is thought to be the feeder of the sheet. The main rock of the sheet is a shonkinite, full of rather automorphic augites, while that of the dike is a much denser basalt.

Specimens of fine compact shonkinite or basalt collected on Alder Creek above the ranches were derived from intruded sheets in the Cretaceous beds above and were mapped later by Mr. Weed.

The most striking instances of intrusive sheets in the Highwoods, however, are those found in connection with the laccoliths of Square Butte and the Shonkin Sag, and will be described in connection with these laccoliths.

DIKES.

INTRODUCTORY.

Beyond question there is no feature of geologic structure in the Highwood Mountains of greater interest than the systems of dikes. Except, perhaps, the laccoliths on the east, which are so well dissected and exposed for study, the dikes are the most striking and characteristic phenomenon of this volcanic area. They were noted by Lindgren and Davis,[a] and their systems and character were mentioned in previous works of Mr. Weed and the writer.

RADIAL DISPOSITION OF DIKES.

The most characteristic feature of the dikes is their general radial disposition around the mountain mass. This is clearly seen by a glance at the geologic map, but further study shows that the great

[a] Tenth Census of the United States, vol. 15. Mining Industries, Washington, 1886; Relation of the Coal of Montana to the Older Rocks, by W. M. Davis, p. 709; Eruptive Rocks, by W. Lindgren, p. 724.

majority fall into several distinct systems; that they radiate not only in a general way about the mountains, but also about distinct loci, and that each locus is a body of granular igneous rock—the former canal of a volcano and a center of upward force and eruption. These facts are shown on the accompanying map (Pl. III), on which the actual directions of the exposed dikes are shown by the colored lines. Most of the dikes cluster about the Shonkin and Highwood peaks as centers, especially the former. Around the outer flanks of the mountains the radial arrangement of the dikes was noted as they were mapped, and the existence and character of the Shonkin stock suspected and its place located by Mr. Weed and the writer before it was visited by Mr. Weed, who was then able to prove the correctness of the supposition. It has long been known that dikes radiate about eruptive centers, especially on the dissected flanks of the volcanoes. The value of this arrangement as a means of locating eroded eruptive centers was shown by Iddings in his work on the Crandall and Haystack[a] areas of the Absaroka Range to the south.

A radial arrangement of dikes and the principles of magmatic differentiation which have been evolved in recent years may be useful instruments in determining the geologic structure in certain cases.

If all the dikes in the Highwoods could be carefully mapped on a large scale this arrangement would be much more pronounced than it appears on the map. On account of the small scale of the map, the limited time available, and, more especially, certain reasons connected with the exposures to be mentioned later, only a part of the dikes actually existing are shown.

CHARACTER OF THE DIKES.

In many cases the dikes have proved more resistant to erosion than the Cretaceous beds they have penetrated, and now protrude as rough stone walls or "reefs." This is more especially conspicuous in the outlying foothills and open bench lands, where there is no vegetation to obscure them save a nap of short yellow-brown grass. An especially noticeable locality is near the head of Byrnes Creek, north of Mann on Otter Creek, and south of the mountains. Here a dike with a north-south trend toward Highwood Peak runs across the open country for miles. It is divided into massive blocks 3 to 4 feet on a side, which have the regularity of placement often found in dikes, which gives them an appearance of artificial construction, like masonry. Although only 8 to 10 feet wide, the wall often has a height of 10 or 15 feet for some distance. The rock is an extremely dense and heavy Highwood minette (shonkinose).

Similar dikes forming heavy projecting walls are found on the bench lands south of the mountains, in the basin of the south fork of

[a] Geology of the Yellowstone National Park: Mon. U. S. Geol. Survey, vol. 32, pt. 2, 1899, pp. 224-231.

Aspen Creek, and on the grassy slopes of the divide in Highwood Gap, where they constitute the chief geologic feature. Other excellent examples are the great wall dikes east of the Shonkin Sag laccolith and near the stage road from Fort Benton to Lewistown and the great reef dike running from Palisade Butte to Square Butte. The greatest number are found on the open foothills and bench lands and upper slopes east of the Shonkin stock, where they were studied and mapped by Mr. Weed. From the top of Palisade Butte 70 are in one view. In all the cases mentioned the rocks composing these dikes are black, heavy traps of various kinds, as described later. The width of the dikes in these cases is usually 6 to 10 feet. It is rarely so great as 20 feet.

In some cases the dikes have weathered more rapidly than the sediments, and the courses of a few are shown by shallow trenches. In these instances the soil produced by weathering is often richer than that of the adjoining sediments, appears to hold moisture better, and supports a heavier, greener growth of grass or a different kind of vegetation. The course of the dikes is then marked on the open, brown hill slopes or level bench lands by greener bands. To one looking down from the height of South Peak they appear like long green pen lines on the surface of brown paper, and their radial trend is clearly seen.

These dikes are usually composed of mica traps or Highwood minettes, which are less resistant to weathering than the other varieties of the rocks found in dike form. They have produced a greater or lesser degree of metamorphism, depending on their size and number. In some cases, as in a weathered dike near the Thornton ranch on Williams Creek, the sandstones have been altered in narrow zones to quartzite, which resists erosion so that it gives a line of two parallel outcrops on either side to mark the course of the weathered dike. The same phenomenon was seen also in the dikes cutting outward through the adinole zone surrounding the Middle Peak stock, where trenches or gaps in the metamorphosed rocks mark the site of the weathered dikes.

On the upper mountain slopes there are undoubtedly great numbers of dikes which could not be mapped with certainty. Their occurrence is marked only by small rock heaps and outcrops here and there. Since the exposures of the dense rocks of the extrusive flows are so nearly like those of the dike rocks that the difference between them can be told only by careful field study and comparison of hand specimens, the accurate plotting of a network of these dikes would have taken an amount of time which would not have been warranted by the results to be attained. This refers especially to the dikes of analcite-basalt (monchiquose) occurring on the slopes covered by breccias and flows of similar rock. Even in many cases where the dikes occur among sedimentary rocks they are often mingled with small patches and remnants of flows.

It is certain, however, that the greater part of those occurrences, which are clear and undoubted, have been mapped, and they are so numerous that the addition of even a considerable number could add nothing more to what is already known concerning their character and geologic significance.

ROCKS COMPOSING THE DIKES.

For field purposes and mapping the dikes may be considered as composed of rocks of two main groups—light-colored feldspathic rocks, feldspar porphyries (salic type), and dark-colored basaltic ones, "traps" or basalt porphyries (femic types). Under each of these groups there are several distinct varieties, whose petrographic characters are given in detail in a later chapter, but which are here briefly noticed as an aid to their recognition in the field and to an understanding of their geologic relations.

LIGHT-COLORED FELDSPATHIC (SALIC) DIKES.

As in the intrusive sheets, the light-colored feldspathic dikes are few in number, not of great size, and, except from the petrologic point of view, of relatively small importance. Near the Curry ranch, where Arrow Creek debouches from the mountains, and in the basin of Aspen Creek they are composed of pale-brown rocks of trachytic character with hornblende phenocrysts. They occur also on the edge of the Shonkin stock on the main divide between Highwood and Shonkin creeks, where the north ridge of Twin Peaks begins, on the point above the Arnoux stock, on the slopes leading up from Highwood Gap to the Highwooden-South peaks ridge, and at the edge of the Middle Peak stock. These are light-gray or brown porphyries with embedded phenocrysts of feldspar, usually large, flat, tabular in shape, and with small black augite prisms. They are syenite-porphyries, largely composed of alkali feldspars. The dikes vary from 6 to 10 feet in width.

The most important feldspathic dike is the great wall dike in the valley of upper Highwood Creek, about a mile below the divide. This dike is gray, and although somewhat variable, averages about 12 feet in width. It trends toward Highwood Peak. It is massive but somewhat plate-like in structure, and has a sort of contact-like crust composed of very short, small prisms, under which the rock is somewhat crumbly. It contains numerous inclusions of dark-colored rock an inch or so in diameter, brought from below, and cuts dark basaltic breccias which are considerably indurated. At a distance it appears as a great light-colored wall running down the eastern slope to the stream, and is a very noticeable object. The rock is a light gray-green with numerous small-white feldspar phenocrysts. It is a peculiar tinguaite-porphyry (highwoodose).

DARK BASALTIC (FEMIC) DIKES.

For field purposes the dark basaltic dikes may be divided into three classes according to the character of the prominent phenocrysts. In each case the base or groundmass is more or less dense and ranges in color from dark stone gray to black. The first class contains prominent phenocrysts of biotite up to half an inch in diameter and is composed of mica traps or minettes of Highwood type (phyro biotitic shonkinose). The second class has prominent phenocrysts of rather large, well-formed black augites and is composed of augitophyres or augite-basalt-porphyry. The third class contains prominent phenocrysts, showing round, octagonal, or hexagonal cross sections of a white mineral which may be altered leucite, but in some cases is analcite, which is held to be often of primary origin.[a] This type may be termed, in accordance with Lindgren's suggestion, analcite-basalt. It is monchiquose.

There are few feldspathic dikes, as previously stated, and their occurrences have been given. In this section what is said of the dikes in general refers to the basaltic dikes, which are found in such numbers that it would be useless to try to give specific details of particular occurrences. In so far as individual occurrences present matters of petrologic interest these are treated in the petrographic portion of this work.

RELATIVE AGE OF THE DIKES.

There have undoubtedly been several periods of dike intrusion, and the different centers have had their own periods of formation. This renders the relative age of the dikes more or less doubtful, but in general it may be said that the feldspathic dikes cut basic breccias; that in one instance on the west side of Highwood Gap an acidic dike is cut by a basic one, and that the basic dikes cut flows and breccias of all periods and also one another, as at Highwood Gap, as shown in the accompanying rough sketch map (fig. 3). Another excellent example is seen in the bluff on the east side of Highwood Creek below the mouth of the branch creek which drains the north slopes of Arrow Peak. The dikes here cut basic (femic) breccias and one another.

Other examples of the intersecting basic (femic) dikes are found in many places, as on the southern slopes of South Peak, where three intersect at one point and form a star. It is evident that the dikes not only occur, in the main, radially disposed around the centers of eruption, as previously described, but that locally also they may

[a] Lindgren, W., Eruptive rocks from Montana: Proc. California Acad. Sci., ser. 2, vol. 3, 1890. Pirsson, L. V., Monchiquites or analcite group of igneous rocks: Jour. Geol., vol. 4, 1896, p. 679.

trend in different directions and intersect in a variety of ways. Further conclusions regarding their origin and relations are deferred until the general history of the district is discussed.

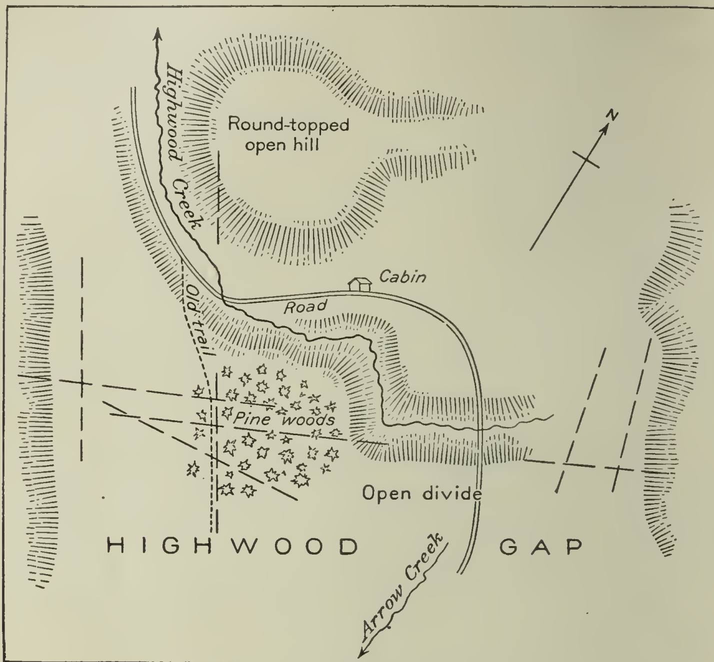

FIG. 3.—Sketch map of dikes at Highwood Gap.

EXTRUSIVE FLOWS AND BRECCIAS.

AREAL DISTRIBUTION.

In a very rough way the lower limit of a major part of the piled-up extrusive material is defined by the 5,000-foot contour around the mountains. Above this, with the exception of Highwood Peak, all of the highest summits and ridges of the group are composed of flows and breccias. The ridges, such as Pinewood Peak on the west and the great main mountain mass running northward through Lava and Arrow peaks and terminated at its northern end by Twin Peaks and North Peak, are almost entirely made up of these ejections. In some places, however, they reach down to 4,000 feet, as at the debouchment of Highwood Creek on the north side and in the valley of Davis Creek on the southeast. The sedimentary strata are found, however, also in the higher mountains, as in South Peak. These facts are of importance because they show that the eruptions have taken place over a country of irregular relief and that a great amount of erosive dissection has taken place.

FELDSPATHIC EXTRUSIVES OF THE FIRST PERIOD.

Volcanic activity began by the extrusion of heavy flows and explosive breccias of feldspathic type. These flows are petrographically between trachytes and andesites; in fact, they are trachyandesites and are described on page 160, under the name of adamellose. They occur not only in the flows as firm, dense rocks of felsitic character, but also as explosion breccias made up of angular lapilli with cement of finer material, and as tuffs and compacted volcanic ash. The greater part of this feldspathic material is found around Highwood Peak. A particularly prominent flow of it occurs on the north side, its lower part forming a marked bench. Highwood Creek just before it debouches out into the wider valley, cut in the soft Cretaceous beds, cuts through the lower end of this flow and forms a small canyon, through part of which the road passes. Other excellent exposures of these heavy flows are found on the north side of Pinewood Peak, especially on the slope leading down into the valley of North Willow Creek, where was collected the material which has served for the analysis of this type. Feldspathic flows and breccias occur also on the south side of Highwood Peak, in the basin at the head of Little Belt Creek. These rocks are light gray to brown in color, dense and felsitic in appearance, with small phenocrysts of mica or hornblende; sometimes by oxidation of the iron-bearing components they are of a deep mahogany red. The breccias are in part explosion breccias and in part, as shown by their structure, flow breccias. The finer materials produced by explosion—the tuffs—are found in the higher ridges; for example, on the ridge between Middle and Highwood peaks and on the ridge around the heads of Davis and Aspen creeks.

The natural deduction from the distribution of the trachyandesite (adamellose) lavas and breccias is that the center from which they were ejected was at Highwood Peak. The arrangement and dip of the flows and heaviest material immediately around Highwood Peak and of the finer and thinner at a distance point clearly to this conclusion.

Succeeding this period of eruptive activity came one of quiescence and erosion, during which the core that had undoubtedly been formed was largely cut away. This is shown by the fact that the succeeding basaltic ejections fell upon a country of irregular relief, spotted here and there with patches or erosion remnants of the trachyandesitic lavas and breccias. For instance, at the north foot of Highwood Peak, on the north side of Highwood Creek, the basaltic extrusives rest directly upon the Cretaceous beds, while a short distance to the south, across the creek, are heavy flows of the trachyandesitic lavas. The latter and the breccias and tuffs could not have extended so far in other directions and not have covered the surface so near the center of activity. If the basaltic outbreaks had immediately succeeded the earlier feldspathic ones the feldspathic rocks should be found in this locality under the basaltic flows. The feldspathic rocks are absent, however, and consequently they must have been removed by erosion before the outbreaks of basaltic material took place. The same is true in other localities.

BASALTIC EXTRUSIVES OF THE SECOND PERIOD.

The second and last period of eruptive activity gave rise to material very different in character from that ejected in the preceding period. While there is a great difference between the types of this period, due partly to mineral composition and partly to texture, they have common features which sharply distinguish them from the feldspathic lavas and breccias of the first period. They are dark, heavy rocks, rich in ferromagnesian components, in augite and olivine especially, and sometimes in biotite. They belong distinctly to the basaltic group of rocks. They vary somewhat in feldspathic components, but none possess plagioclase feldspars and none are of the type of common basalt. Commonly, when they are compact rocks, there are embedded in them more or less rounded white phenocrysts, which often have more or less distinct octagonal or hexagonal outlines. In such cases they appear like the dike and sheet rocks previously mentioned, and indeed in many cases it would be impossible to distinguish the two rocks. They have also a very striking resemblance to the leucite rocks from Italy and from Lake Laach, in the Eifel district in Germany. In some cases the white component is a very fresh analcite, and these rocks are analcite-basalts, like those in the dikes. But in many other cases the white portion is composed of variable white minerals of feldspathic nature, and the rock may then be pseudoleucite-basalt. A very careful search was made for unaltered leucite in these rocks, but with the exception of one or two doubtful cases it could not be found. It seems most probable from the shape of the crystals and their general relationship to these magmas, rich in potash, that they were originally leucite, but further consideration of this question is deferred until the petrography of the basaltic lavas is taken up.

Like the intrusive rocks, the extrusives of this period generally carry numerous phenocrysts of well-formed black augites and olivine, the latter often altered to a red pseudomorphous mineral.

The breccias and tuffs of this group are dark, chocolate colored, or brown rocks running into distinct dark-purple shades in the finer tuffs. They carry fragments of basaltic rocks and are generally greatly altered and the iron-bearing components oxidized. The fragments are sometimes green, sometimes purple, and mingled with them are pieces of black shale occasionally hardened to slaty forms. In some cases the fragments are angular, true lapilli forms; in others they are rounded, producing volcanic conglomerate. In the localities visited there was no evidence that they are water-laid.

Slaggy scoriaceous forms were found in the lavas, especially on the higher crests, as at Lava, Arrow, and Pinewood peaks. On the Lava-Arrow peaks ridge great quantities of very vesicular lava and of rounded "bread-crust" bombs were observed. Amygdaloidal forms are also common, the amygdules reaching half an inch in diameter in some occurrences. The amygdules are usually compact, with fibrous structure, consisting of various zeolites, natrolite, stilbite, etc. Sometimes, as on Pinewood Peak, the vesicular rock is full of the pseudoleucite mentioned above, and the vesicles are filled with small amygdules of about the size of shot. In such cases it is not easy to distinguish them; the rock then appears crowded with white minerals.

Distribution of basaltic extrusives.—As may be seen by reference to the geologic map (Pl. III), most of the higher peaks and ridges are made up of basaltic extrusives. Highwood Peak and the ridge running south to South Peak are practically the only exceptions to this rule. In Arrow Peak the basaltic extrusions reach their highest elevation. They form two large areas, one on the east, the other on the west of Highwood Peak, and at these places rest on trachytic (feldspathic) extrusives of the former period. They form the great central area of the mountain group, resting in part on the earlier lavas and breccias and in part on Cretaceous strata. They have been greatly eroded and are also found to the north in isolated patches of considerable size. A view of the mountain masses at the head of Davis Creek, composed of these volcanic ejections, is shown on Pl. II, *B*, which is reproduced from a photograph by Mr. Weed.

SOURCES OF THE EXTRUSIVE ROCKS.

In considering the possible sources of the various flows, breccias, and tuffs of the two periods, there are certain general facts which must not be lost sight of. In a volcanic area which has suffered little or no erosion the cones give as a general rule all the testimony that is needed in this direction. In the Highwoods, however, great erosion has taken place and the cones have been so much cut into and carried away that the remnants afford only partial evidence for their reconstruction, and additional data must be sought in other directions.

When a column of molten magma rises through its conduit to the upper portions of the earth's crust it gives rise to volcanic action. After the volcano has become extinct and erosion has progressed far enough there will be uncovered a stock of massive rock—the solidified and crystallized magma column of the conduit—which is generally surrounded by a complex of radial dikes and intruded sheets. This complex cuts into, or at a greater distance is surrounded by, still uneroded masses of flows, breccias, and tuffs. Such phenomena have been described by Iddings at Electric Peak[a] and on Crandall Creek[b] in the Absaroka Range and by Mr. Weed and the writer at Castle Mountain, Montana.[c] Examples in other regions are also well known.

In the Highwoods there has been apparently a number of such centers of eruption, and it is difficult to determine what share each may have had in this work. As previously mentioned, the weight of evidence tends to show that the feldspathic lavas were erupted at Highwood Peak, as at this place the stock of granular rock most nearly agrees in chemical and mineralogic characters with the lavas, as may be seen by reference to the petrographic descriptions (pp. 60, 160, 191). The correspondence is not exact, of course, but an absolute chemical correspondence between a stock rock and the related extrusives is scarcely to be expected, although it may occur. Considerable divergences are noted between successive outflows of the same period, and may be caused by progressive processes of differentiation in the liquid mass below. The discussion of this subject is postponed to a later chapter. Both field evidence and petrographic relations indicate that the Highwood stock was the source of the feldspathic extrusives.

The basaltic extrusives probably were erupted from several centers. The chemical correspondence is here very close indeed if the rocks composing the Shonkin, East, and Arnoux cores are compared with the basalt selected for analysis. It seems almost certain that a large part of the basaltic extrusives of the central and northern part of the area have had their origin at the Shonkin stock center. The arrangement and bedding of the stock and the character of its south portion, which consists, according to Mr. Weed, of a tumultuous agglomerate of coarse-grained blocks in a finer-grained cement, are strongly confirmative of this. The evidence in regard to the other stocks is not so clear, and they may or may not have been centers of eruptive activity.

The basaltic flows and masses around Highwood Peak point to a renewal of activity at this center after the period of feldspathic lavas, since it seems difficult to refer those of Pinewood Peak, for example, to the distant stocks of the central area. The flows might be the surface outpourings of later dikes, but the character of much of the material indicates explosive action. If they are referred to this center there were, first, outbreaks of feldspathic lava, followed by eruptions of basaltic lavas, and the intrusion of the monzonite stock was succeeded by the intrusion of syenite. The chemical characters of these magmas and their bearing on the petrology of this center are discussed in Chapter VII, p. 190.

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[a] Eruptive rocks of Electric Peak and Sepulchre Mountain: Twelfth Ann. Rept. U. S. Geol. Survey, pt. 1, 1892, p. 569.

[b] Geology of the Yellowstone National Park: Mon. U. S. Geol. Survey, vol. 32, pt. 2, p. 215.

[c] Geology of the Castle Mountain mining district: Bull. U. S. Geol. Survey No. 139, 1896, p. 56.

One point in regard to the origin of the basaltic eruptives remains to be noticed. On Arrow Peak heavy flows of basalt dip downward along its sides in several directions. This and the general character of the peak and its material suggest that the peak may not be a mere remnant of a once lofty cone, whose center of activity was at some distance, but may itself have been a center of activity. Otherwise these flows, whose character and attitude are unmistakable, would have to be attributed to outbreaks of dikes on the sides of an erosion remnant—a not altogether probable supposition. If Arrow Peak represents a center of activity, it is probable that there is, in some part of its base, a mass of granular rock, which is covered by flows and breccias and which erosion will one day bring to light.

CHAPTER IV.

GEOLOGY OF THE LACCOLITHS.

INTRODUCTORY.

The laccoliths of the Highwoods have been described by Mr. Weed and the writer in two previous papers, mentioned in the accompanying bibliography, on the Shonkin Sag and the Square Butte laccoliths. It has seemed best, however, to repeat in abstract the essential portion of these descriptions, partly to make this paper complete and partly because the study of the Shonkin Sag laccolith, made after the paper on Square Butte had appeared, has furnished a key to the interpretation of the structure of this latter laccolith, which the facts obtainable at Square Butte itself do not entirely afford. This has caused a modification of ideas regarding it in several respects, though it has furnished a remarkable confirmation of the views previously expressed. Moreover, while the majority of petrographers have accepted the conclusions drawn in these former papers, in their bearing on theoretic petrology, some have advanced views of their own which appear to the writer to be founded on misconceptions of the facts. It is desired to discuss these and to advance some new conclusions which further study has brought out. To render the discussion more intelligible and convenient a rather full abstract of the descriptive parts of the former papers is embodied in this chapter.

In this eastern extension of the Highwood Mountains the four principal masses of igneous rock are of intrusive laccolithic nature. In addition there are a number of dikes and intrusive sheets. There is no evidence that the forces which elsewhere in the mountains found outer vents and gave rise to extrusive material did so here; the facts all point to the opposite conclusion.

The sedimentary beds into which these rock were intruded are arenaceous shales or fissile sandstones horizontally disposed, except where the intrusions have disturbed them. They are of yielding nature and admirably suited for the intrusion of sheets and laccoliths.

As may be seen by reference to the map (Pl. III), they are cut by two drainage valleys which meet each other at a nearly right angle, that of Arrow River and that of the Shonkin Sag, in whose flat floor a feeble stream, Flat Creek, meanders. The sag is an abandoned channel of Missouri River and is easily traced on the map by the contours, the course of Flat Creek, and the scattered alkaline lakes which now occupy it. The dissection of the land between these two drainages has exposed the laccoliths and sheets.

There are four laccoliths in this area, the major and the minor in the Shonkin Sag, Square Butte, and Palisade Butte.

MINOR LACCOLITH OF THE SHONKIN SAG.

About 2 miles due north of Square Butte, as may be seen by reference to the geologic map (Pl. III), is a mass of igneous rock intruded into the sediments. It is shown as a semicircular area of shonkinite exposed in the west wall of the sag. From the valley below, it appears as a dark cliff, perhaps 100 feet in height and a few hundred yards long. It has a columnar structure, and from the foot of the cliff a talus slopes down to the valley. It is clearly intrusive in the sandstones, and although not a symmetrical laccolith it is evidently of laccolithic nature. The rock composing it is similar to the shonkinite (shonkinose) of Square Butte. While not of great importance it has a certain interest and value, as it is another example of laccolithic intrusion, and by its confirmative testimony helps to explain the nature of the other masses, such as Square Butte and Palisade Butte, where the evidence concerning the character of the intrusion is not so clearly shown.

MAJOR LACCOLITH OF THE SHONKIN SAG.

The Shonkin Sag turns west at the small laccolith just mentioned, and about 3 miles from it in the north wall of the valley is the section of the main laccolith described by Mr. Weed and the writer. From the opposite side of the valley an excellent view of it is obtained, and it is seen as a columnar cliff about a mile long, with an even and regular face, interrupted about the center by a deep canyon-like gulch which cuts through the whole cliff. The columnar structure is pronounced, the polygonal columns having a diameter of 2 feet or more and an estimated height of over 100 feet, which is also the thickness of the laccolith along the cliff front. All along the front are seen the horizontal light-brown Cretaceous sandstones which form the floor upon which the laccolith lies. The regular, even level of this floor is very noticeable. Extending from the foot of the cliff to the valley is a great talus which is cut at intervals by rain-washed ravines. The detrital material reaches nearly or quite to the foot of the columns, and the sandstones beneath the laccolith are in places nearly concealed, but in the intervening ravines a considerable thickness of them is seen. On top of the laccolith are the horizontal, unbroken Cretaceous sandstones into which it is intruded. Their thickness is variable, as from each end of the cliff wall it gradually diminishes; about the middle, where the laccolith is cut by the intersecting gulch, the sandstones disappear and leave, especially on the eastern side, a portion of the top of the laccolith bared. On the opposite side of the gulch, however, a considerable thickness of them rests on top of the columns of igneous rock.

Ends of the laccolith wall.—From what has been said above, it is clear that this cliff wall is the cross section of a flat mass intruded into and lying between the beds of sandstone, its laccolithic character being seen only at the outer borders.

The main body of the laccolith at the eastern end thins out until it becomes only an intrusive sheet not more than 10 feet in thickness, which on the same horizon extends a great distance into the sandstones. In addition to this main lower fringing sheet there are two

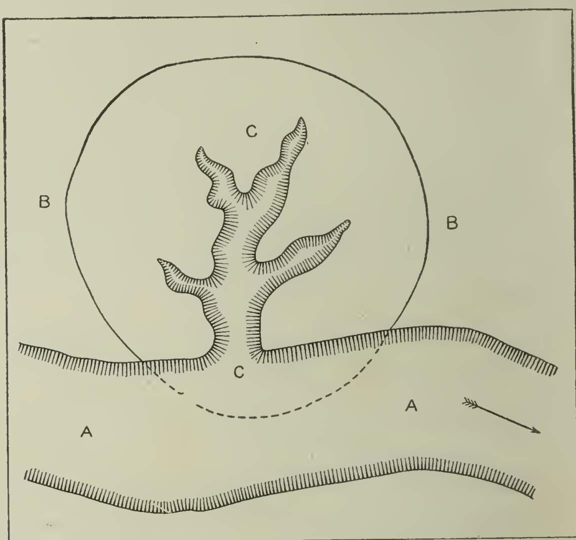


FIG. 4.—Plan of Shonkin Sag laccolith. A, former course of Missouri River; B, laccolith; C, gulch.

or three lesser ones, which do not extend far and quickly die away in the sedimentary beds.

At the western end the relations are less clear. The valley wall has been broken down and eroded somewhat, so that there is not the same vertical cut, but the exposures are sufficient to show that the structure is less typical, the beds having been affected to some extent by rupturing. The laccolith, however, frays out in thin, fringing sheets and the basalt sheet, to which it thins down, has the same thickness and character as on the other side, and may be traced, always at the same level horizon, among the sandstones several miles up the valley. The persistency of the thin sheet of which the laccolith is a greatly thickened portion is remarkable.

The laccolith rock.—The rock composing the outer fringing sheet is dark colored, has a dense texture, and is dotted with crystals of black augite and round white spots of an altered leucite. It may b called a leucite-basalt. The lower 12 to 15 feet of the great columns of the main body of the laccolith are also composed of this rock, which then passes into a fully granular rock of granitic texture, consisting of augite, olivine, biotite, and orthoclase, like the shonkinite of Square Butte. At the top the columns again pass into the porphyritic leucite-basalt.

Interior of the laccolith.—It has been mentioned that the central portion of the laccolith wall is broken by a stream gorge which has cut through the laccolith into the underlying sandstones. The stream gradually rises above the sandstone until it flows over the igneous rock, and at the same time it is joined by tributary gulches, so that the whole interior of the laccolith is thoroughly dissected and laid bare.

Ascending the gulch, one soon comes to the contact of the igneous rock and the underlying sandstones. The fissile, platy sandstones at the contact are changed to a dense, flinty, blue rock, which generally has a thickness of a few inches and never more than about a foot. The igneous rock at the contact is dense and dark and is filled with augite and altered leucite phenocrysts; it is similar to the rock in the outer columns described above. It maintains this character for about 15 feet and then passes into an evenly granular, coarse-grained shonkinite. This has a columnar parting, which, as one approaches the center, is less evident than in the outer cliff wall. The drainages now lose their canyon-like character and widen out into V forms with broader spurs between them, often showing wide expanses of naked rock.

The shonkinite has a thickness of about 75 feet and is succeeded by a rock of different character. There does not appear to be any contact between the two, but the shonkinite in a little distance passes into the new type. This is a much lighter colored rock of a coarser grain. It is composed of large augites, many of them 1 to 2 inches long, often radiating from a common center in such a manner as to form stars, and of equally long but slender foils of biotite, with the interstices filled with white feldspars or feldspathic material. This rock was always found in a weathered and crumbled condition. This layer or zone is about 15 feet thick and passes above into a white syenite of medium grain, specked with augite crystals. This has a rather thin, horizontal, platy parting, by which it splits and weathers into piles of plates. On a clear day the decided contrast makes the syenite seem white and the dark shonkinite appear black, especially when the two rocks are seen in large masses.

This syenite resists weathering much better than the crumbly transition rock mentioned above, and has therefore determined the shape of curious and fantastic rock piles along the line of the outcrop. These piles commonly take the form of a mushroom or stool, in which the outspreading top is formed of the syenite, while the stem is composed of the transition rock.

The thickness of the platy white syenite is about 25 to 30 feet, and above it passes within a short space into the same coarse, crumbly transition rock that occurs below it. Here, however, the transition rock is only about 5 feet in thickness; it then passes into a coarse shonkinite like that below, which in about 5 feet begins to be denser and blacker, and in about 5 feet becomes a porphyritic rock spotted with augites and altered leucites—the same leucite-basalt as at the bottom.

The top of the laccolith is an elevated plateau, which has a marked turtle-back form and is cut in the center by the gulches which merge into the dissecting gorge. Except around this basin it is covered with the overlying sediments, but here the top of the igneous rock is exposed.

Cause of dissection.—From the presence and character of the morainal drift it is evident that during the Glacial epoch the continental ice sheet in this region pushed its way as far south as the lower slopes

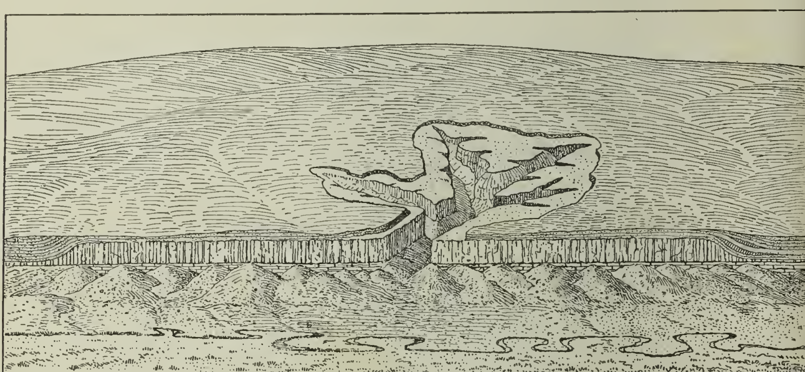


FIG. 5.—Stereogram of Shonkin Sag laccolith.

and foothills of the Highwood Mountains. The Missouri River was driven southward and forced to flow around the foot of the ice front. In doing so it excavated the valley of the Shonkin Sag and thus sawed down and through the outer circumference of the laccolith. The position of the intersecting tributary was previously determined and the ice moved over the already eroded surface of the laccolith. At the close of the Glacial epoch the river retreated to its present position, and since then erosion has deepened and extended the dissection. The relative positions of the former Missouri Valley, the laccolith, and the dissecting stream are shown in fig. 4, which represents them in a diagrammatic ground plan. In fig. 5 is given a stereogram of the laccolith, in which the various points mentioned are shown in a diagrammatic way. The dotted surface at the top represents in a general manner the area bared by erosion.

Internal structure.—From the description which has been given, it is clear that the outer portion of the laccolith is different from the interior in character and in the type of rocks composing it. The differences may be concisely summed up in the following section, which is approximately correct:

Section of laccolith.

	Center.	Outer wall.
	Feet.	*Feet.*
Leucite-basalt-porphyry	5	10–15
Dense shonkinite	5	
Shonkinite	5–6	
Transition rock	3	
Syenite	25–30	
Transition rock	15	
Shonkinite	60–75	75
Leucite-basalt-porphyry	15	15
Total (approximate)	140	100

From these data a cross section of the laccolith can be constructed which will have the appearance shown in fig. 6.

FIG. 6.—Cross section of Shonkin Sag laccolith. Vertical and horizontal scales the same; white indicates syenite and transition rock; black indicates shonkinite.

In fig. 6 the vertical and horizontal scales are the same, and the sheet-like or flattened shape of the laccolith is shown. The transition rock and the syenite are shown in the white portion of the section. Their vertical thickness is known, but their horizontal extension is from necessity largely conjectural, since there is known only the distance from the center to the outer cliff wall, as revealed in the dissecting gulch.

The writer's conception of the laccolith and the structural relation of its interior parts would be represented by the figure of revolution which would be generated if the cross section were revolved upon a perpendicular drawn through its middle point. It is true this would cause the laccolith and the successive shells and syenite kernels to be also circular, to have a common center, and to become a true circle in ground plan. It is not known that this is exactly the case. The laccolith, the interior shells, and the kernels may be more or less ellipsoidal or irregular in outline. They probably do not have exactly common centers and the same thickness everywhere. Nevertheless, these are mere details which are believed to be of little importance in comparison with the idea that the figure would express the generally circular, concentrically zonal arrangement of the parts.

The discussion of the bearing of these conclusions on theoretical petrography and the origin of the various rock types is deferred until a later chapter.

PALISADE BUTTE.

Palisade Butte is less than 2 miles west of Square Butte. It stands isolated upon the open country, and forms, like Square Butte, a prominent landmark. It rises about 800 feet above the plain, and its outline against the sky resembles the weathered stump of a tree. On all sides is a long talus slope, in great part covered with soil and grass and broken here and there by low outcrops and masses of rock, which leads up with increasing gradient from the plain to the bare cliffs of massive rock which compose the main mass. Above these cliffs are again steep slopes interrupted by cliffs.

The walls are remarkable for the regular columnar structure of the rock. The hexagonal columns are, on an average, about 18 inches in diameter, though often greater, and divided by regular cross joints. Where they occur they extend the whole height of the exposures, in places a distance of 100 to 150 feet, but it is evident that originally they must have extended through the whole of this portion of the igneous mass, as in the Shonkin Sag laccolith, and therefore may have been several hundred feet in length. Their character is shown in Pl. IV, *A*, from a photograph by Mr. Weed.

The rock composing the columnar portion of the butte and the outcrops in the talus is shonkinite. On exposed surfaces it weathers to a dark color, giving the cliffs a somber and gloomy character.

The butte is crowned at the top by a large mass of a light-colored rock of platy, laminated character. This is an augite-syenite, much like that in the Shonkin Sag laccolith. It weathers with a lighter color than the shonkinite on account of the preponderance of feldspar over augite, and the contrast between the two, while not pronounced, is striking.

The mass of syenite, which has a considerable thickness, is roughly wedge-shaped, with a cliff of some height toward the south and a slope toward the north. On the south side the rock, with its platy horizontal parting, is clearly seen resting on the massive columnar shonkinite, but toward the north the relations are less clear, because the butte to a great degree loses its precipitous character and slopes down in talus masses toward the plain, with the broken-down rock masses intermingling.

Rock variation in Palisade Butte.—The rock composing Palisade Butte shows the same variation as that found in Square Butte and the Shonkin Sag laccolith, only it is not so sharply expressed. In the low outcrops which rise through the talus slopes and are farthest from the butte the rock is very rich in augite and therefore dark and femic like that of Square Butte. As one approaches the butte an increase in feldspathic components is observed, and the rock of the columnar

A. COLUMNS OF SHONKINOSE, EAST SIDE OF PALISADE BUTTE.

B. VIEW IN ZONE OF EROSION MONOLITHS, SQUARE BUTTE.

cliffs is perceptibly different from that of the lower outcrops. In the syenite of the platy mass on top this difference is, of course, much more marked; the rock is not so strikingly salic as the syenites of Square Butte and the Shonkin Sag laccolith, but it is still a syenite.

Thus the same order holds as in the other laccoliths—a basic outer and lower mass, and above a more feldspathic upper inner portion. There has been, therefore, the same kind of differentiation as in the other laccoliths, only it is more gradually expressed.

Laccolithic character of Palisade Butte.—The position, structure, and rock relations show that Palisade Butte is a remnant of a laccolith formerly of greater size.

It is to be noted that a heavy dike of dark femic rock of monchiquoid habit (shonkinose) runs out from the eastern side toward Square Butte. As shown elsewhere, this dike has the same chemical character as the shonkinite, of which the greater part of the butte is composed. It is thus possible that this dike may have been the source of the igneous material, especially since the present mass is evidently only a remnant of a much greater one which formed the original laccolith. In this connection it may be observed that the sedimentary beds of the plain on this side are hardened and toughened, with fragments and patches of black, dense femic rock, which may possibly be remnants of the laccolithic floor in this direction.

SQUARE BUTTE.

Introductory.—In size and conspicuous position Square Butte is the most important of the laccoliths of the area. That it was known to the early explorers may be inferred from the remarks quoted in the historical summary given in the beginning of this bulletin. The exploratory work of Davis and Lindgren evidently did not lead them in this direction, since they give no description of it. Previous to the former paper by Mr. Weed and the author, the only article relating to Square Butte of which the writer has any knowledge is one by Lindgren and Melville,[a] in which is given a petrographic description of material collected there by Dr. C. A. White. The butte is described as being composed of a light-gray eruptive rock having a distinct lamination, with several sheets of a dark volcanic rock intruded in the sediments around its base. This is presumably from a note furnished the authors by Doctor White, who had passed under its base a number of years before, while on a trip collecting fossils in company with the late Prof. Jules Marcou.

General description of Square Butte.—Square Butte is a circular mass resting on the point of the table-land at the junction of the Arrow Creek and Shonkin Sag valleys. The platform consists of nearly horizontal shales and sandstones, which on three sides are

[a] Am. Jour. Sci., 3d ser., vol. 45, 1893, p. 286.

deeply trenched by stream gulches descending from the base of the butte into the larger valleys below. On the western side an open plain stretches from the base of the butte toward Palisade Butte and the breccia foothills of the main mountain group. It is the dominating feature of the scenery in this part of the region, and forms a prominent landmark from the open level country to the north and east, its dark base and white crown making it conspicuous for a long distance. Its name is derived from its flat top.

The trenched table-land on which the butte rests has a height of 4,000 feet above sea level, and the mass of igneous rock rises 1,700 feet above its pediment, making the altitude of the upper surface about 5,700 feet. The slopes are at first gentle, but become steeper, and at the top, on all sides, is a precipice perhaps 200 feet high. In a few places this escarpment is cut by small, narrow gulches. The summit is nearly level, elliptic in outline, and nearly 1 mile across in its greatest length.

The symmetric form of the butte is rather remarkable. It presents from nearly every point the appearance of a very short section of a huge cylinder resting on a low, broad, truncated cone. This regular arrangement is interrupted only on the southwest side, where a short tongue-like protrusion of the mass occurs.

Laccolithic origin of Square Butte.—Square Butte is composed entirely of igneous rock. Above the sandstones of the table-land no sedimentary rock whatever is seen. Near the immediate contact of the igneous rock with the sedimentary strata the sandstone beds curve up sharply on all sides. Below this, where the trenching by the streams has gone on, the sandstones have been cut into and the intrusive sheets which form a peripheral fringe around the mountain are brought to light. These relations are shown on the map, Pl. III, and in the cross section, fig. 8.

The form of Square Butte, the ring of upturned sediments around it, and details of structure, which will be presented later, make it evident that the butte is a laccolith stripped of its sedimentary cover, but not yet sufficiently eroded to lose its general form. This interpretation of its origin is also supported by the occurrence to the east of Square Butte of the laccoliths in the Shonkin Sag previously described.

Lower zone of dark monoliths at Square Butte.—Square Butte, from every point of view, presents, first, a base of dark, somber slopes, extending nearly halfway to the summit, which in turn are capped by light-colored ones that over great areas are often white. From a distance of a few miles the dark base is seen to be fantastically eroded into jutting towers and spires of rock. This series of strangely shaped monoliths, which surround the lower slopes of the mountain on all sides, die out at about a given height. Above this fringe of pinnacles are seen the white upper slopes, composed of masses and walls of rock which are in marked contrast to the black base.

As one approaches nearer and enters the region of black monoliths, it is found to be a maze of small, partly wooded glens, separated by towering masses and pinnacles of rock which have a height of from 100 to 150 feet in many places and of but a few feet in other places. The attention is immediately arrested by a peculiar and regular platy structure. The masses of rock are built of a series of inclined disks, each a few inches in thickness and oval to subangular in shape, with rounded edges which accentuate the disk-like form. Generally the disks decrease in size from bottom to top, but there are exceptions to this rule, and in these cases strange and weird figures are produced. The plane or hade of the disks is not horizontal, but inclines to the outside in all directions around the mountain, approximately parallel to the prevailing slope, which, indeed, is determined by this platy parting. Their character may be seen in Pl. IV, *B*, which is reproduced from a photograph by Mr. Weed.

The disposition is precisely like the dip and strike of sediments in a domed anticline, and the resemblance at times to sedimentary strata is striking.

Upper zone of white rock at Square Butte.—The monoliths are found over a distance of a mile up the slope. They diminish in size as one goes upward, and a horizon is reached where the rock changes abruptly from the dark, nearly black augitic phase to the white syenite described by Lindgren. In many places the monoliths continue higher, but are made of the white rock. They are smaller in size, but possess the same remarkable disk-like, platy structure, and the disks are perfectly parallel to those of the black variety below.

The transition line between the two rock varieties is extremely abrupt, but it is not of the nature of a contact. The even grain continues throughout, but in the space of a few inches or a foot or so the black augite begins to diminish and finally disappears, hornblende occurs, the rock assumes a more feldspathic character, and rapidly passes into the syenite which was described by Lindgren and which constitutes the main inner mass of the mountain. There is thus a narrow mottled zone between the black and the white rocks.

The monoliths which lie near the transition zone are sometimes black disks resting in place on white rock below; the transition band sometimes passes through them and they are black disks resting on white ones, or it passes through the disks almost vertically, so that one part of each disk is white and the other black.

The facts just presented are to be carefully noted, because they show that however much the two varieties of rock may differ and however abrupt may be the change from one into the other, they were not formed by two separate intrusions, but on the contrary are a geologic unit, and that the mass as a whole was intruded at one and the same time, and cooled and crystallized under the same conditions, and that the explanation of the peculiarities which it presents must be sought in another way—one which has an important bearing on theoretic petrology.

As one approaches the top no more black rock is seen; the remainder of the mass is of white or pinkish syenite and presents everywhere the same even grain. The same platy structure continues, and at times there are no talus slopes, vegetation, herbage, or even soil, only smooth, white surfaces of naked rock, on whose almost polished slopes it is impossible to climb. Toward the top the average thickness of the plates increases somewhat and their dip gradually becomes less, until eventually they are horizontal. The ring-shaped precipice which forms the top has been caused by breaking off of the horizontal plates. The regularity of this platy jointing, together with the even rounding of the corners through weathering where the joint planes cross, gives a likeness to colossal masonry in the upper walls.

Origin of the platy parting at Square Butte.—From what has already been said in regard to the platy parting which forms so marked a feature of Square Butte, it will be seen that it bears the same relation to the mass as a whole as do the enfolding leaves of an onion to the bulb cut in half by a horizontal plane.

The parting planes are thought to represent parting surfaces parallel to the former covering of the laccoliths, from which the isothermal planes of cooling descended into the mass. The writer can conceive of no other hypothesis which would give a reasonable explanation of their arrangement and disposition; and since Square Butte is unquestionably an intrusive mass, they are regarded as one of the strongest proofs of its laccolithic nature.

Such an arrangement of the parting planes of a cooling igneous mass is by no means unknown, however, as it frequently occurs in the great phonolite domes of central Europe. Ramsay[a] has also described a similar kind of parting in the great mass of alkaline syenitic rocks of Umptek, in the peninsula of Kola, in Russian Lapland, which he regards as of laccolithic character. He also attributes this parting to the fact that the cooling planes caused shrinkage parallel to the outer cover of the mass. He also believes that between the rock layers thus formed later injections of magma of different composition have been forced, like intrusive sheets in sedimentary strata.

Johnston-Lavis,[b] in a short criticism of the former paper on Square Butte by Mr. Weed and the writer, suggests that this parting is not due to shrinkage caused by cooling, but to initial shearing stresses which were due to the forcing of a viscous mass into its present position and which are like that which produces the well-known lamination observed in many lava flows of highly siliceous magmas. This view the writer can not accept, because this platy parting parallel to

[a] Fennia, II, No. 2, 1894, p. 81.
[b] Brit. Assoc. Adv. Sci., Rept. Liverpool Meeting, 1896, p. 792.

the upper outer surface is extremely common both in intrusive masses of all kinds of igneous rocks and in cases where the magmas must have been very fluid at the time of movement and shearing stresses could not therefore have occurred in them. In many cases such masses have at the top a platy parting, which grows thicker below and finally changes to the columnar parting in conformity with the law that the initial major parting takes the direction of least resistance. The mass in which is the celebrated Fingals Cave, and the Shonkin Sag laccolith, previously described, are examples, and if Square Butte were deeply dissected by erosion toward its center it might show an outer platy parting and a deeper inner columnar one. Palisade Butte offers strong evidence on this point, as it has the same structure and thus unites all these three laccoliths together into a similar group. In view of the various stages of dissection in the different laccoliths, it being least in Square Butte, and of the facts just presented, there is no good reason for assuming that the platy parting of Square Butte was produced otherwise than by the usual and well-known one of contraction due to cooling. Square Butte is the largest, cooled the most slowly and regularly, and therefore possesses the platy parting with the most regularity.

The fact that the same parting planes pass through syenite and shonkinite alike is also strongly opposed to the view that they are due to a shearing lamination. And, moreover, since the general study of all the facts presented by these three laccoliths has led to the belief, as shown elsewhere, that the two kinds of rocks found in Square Butte have been produced by differentiation after the intrusion of the magma in a homogeneous condition, it is also believed that the magma was then in a far too liquid condition to have permitted shearing stresses to be set up within it.

Diagrammatic section at Square Butte.—It has been already said that the study of the Shonkin Sag laccolith has caused the writer to modify in some degree his conception of what is the probable interior constitution of Square Butte. The same facts are also to be seen in a less pronounced degree at Palisade Butte, but until after the Shonkin Sag laccolith was studied their true significance was not understood. Square Butte supplies the key and unites all the laccoliths in one group. As the laccoliths are in different stages of dissection, each supplies evidence that is wanting in the other two.

In the previous published section, which may in a simplified form be seen in fig. 7, the syenite was given a very great volume, and the transition zone was placed at the bottom of the laccolith, thus making it consist chiefly of this rock. At that time the conception as to the relative amounts of the two rock types was wholly theoretical, the dissection being no greater than the diagram indicates. Since, however, all three laccoliths consist of the same kinds of rock, i. e., similar magmas intruded near one another at the same time and under similar conditions, and since they are of similar structure, so far as shown by erosion, it is reasonable to conclude that they are essentially similar throughout, though they may differ in minor details of form, size, completeness of differentiation, etc. This being the case, the writer now believes that shonkinite comprises the greater part of

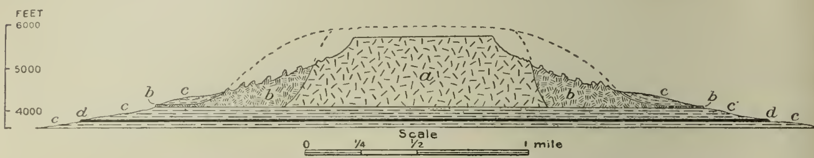


Fig. 7.—Former section through Square Butte. *a*, Syenite; *b*, shonkinite; *c*, sandstone and shale; *d*, underlying sheet. Dotted line shows restoration of laccolith. Vertical and horizontal scales are the same.

Square Butte and underlies the syenite as in the other two laccoliths, and that the relations of its parts are correctly shown in fig. 8. In this connection the geologic map should be consulted.

The protrusion to the southeast on a projecting rock tongue also confirms the above hypothesis, as it shows the shonkinite below, with

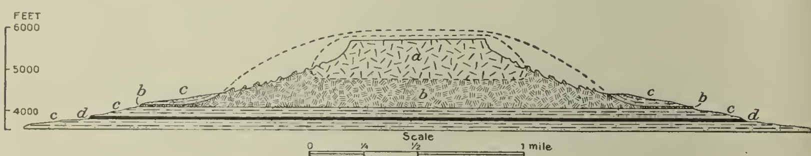
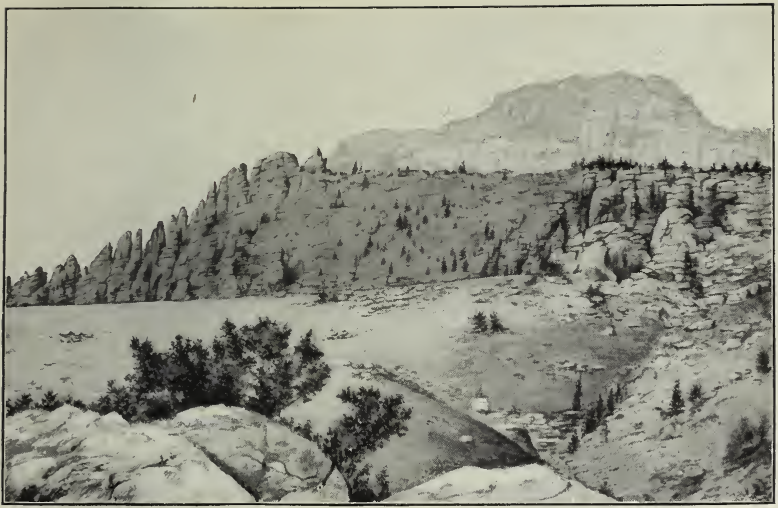


Fig. 8.—New section through Square Butte. New line. *a*, Syenite; *b*, shonkinite; *c*, sandstones and shales; *d*, underlying sheet. Dotted lines show restoration of laccolith. Vertical and horizontal scales are the same.

white syenite above, as seen in Pl. V, *A*, from a photograph by Mr. Weed.

Consideration of the bearing of these facts on the question of the origin of the laccoliths and their relation to the other igneous rocks of the Highwoods is deferred to the last chapter, on the petrology of the area.



A. PULASKOSE (SYENITE) RESTING ON SHONKINOSE, SOUTHWEST SIDE OF SQUARE BUTTE.

B. EAST END OF SHONKIN SAG LACCOLITH.

CHAPTER V.

THE SEDIMENTARY PLATFORM.

INTRODUCTORY.

The sedimentary beds on which the extrusive masses of the mountains rest, and which are cut by the intrusive rocks (see Pl. III), have been described by Mr. Weed in the Fort Benton folio of the Geologic Atlas of the United States. The part of his description which relates to the area shown on the map is here quoted, in order to show the character of the material in which the igneous rocks were intruded. The nature of the sediments has so often influenced the manner in which these intrusions took place that this is an important part in the discussion of the latter. The beds are all Cretaceous.

Cascade formation.—The Cascade formation consists of alternating beds of sandstones and shales. The lowest bed of sandstone, 160 feet thick, is distinguished from the underlying Ellis sandstone [top of the Juratrias] by its dull brownish color, its weathered appearance, and its lamination. Above these sandstones is the coal seam, which in some places occurs near the top of the formation. The sandstones lying immediately beneath it are impure, micaceous, and of a lavender tint. The coal seam is from 5 to 12 feet thick. A massively bedded sandstone that caps the coal seam and forms a sloping table-land over large areas is taken as the top of the formation. The total thickness on Belt Creek is 520 feet. * * *

The fossil leaves found with the coal seam are of Lower Cretaceous age and resemble those of the Kootanie formation of Canada.

Dakota formation.—The Dakota formation consists of beds of sandstone alternating with red and gray shales and clays. Certain purplish sandstones are of variable composition, carrying large amounts of purplish and red shale in streaks or disseminated through the rock. Buff-colored sandstones are purer and are often cross bedded. Some sandstones pass horizontally into clays, and these and the interbedded clays are mostly of a reddish or lavender color, containing lumps of yellow sandy material. At a horizon 140 to 300 feet above the coal of the Cascade formation the red shales contain bowlders and lenses of limestone varying from a few inches to a foot or more in thickness. The rock is dense, blue gray in color, weathering light buff, and contains numerous fresh-water fossils. The sandstone above these fossil-bearing beds is assumed to be the uppermost bed of the formation, giving a total thickness of about 300 feet along Belt Creek.

Colorado formation.—The Colorado formation consists chiefly of leaden-gray shales. The base is not readily separable from the Dakota, as the sandstones of that formation become shaly toward the top and alternate in their layers with the dark clay shales of the Colorado formation. The Colorado comprises two formations, previously distinguished as the Benton shale and the Niobrara limestone. The former is typically developed about the town from which it is named [Benton on the Missouri, about 20 miles north of the Highwoods]: the latter is also a shale formation in this quadrangle, but contains limestone concretions. * * * [In] the Belt coal field the Benton shale consists of alternating strata of gray shale and impure shaly sandstones, a good section of which is seen in Belt Butte. At this locality and along the south base of the Highwood Mountains the formation holds a white ash bed whose rock resembles porcelain and breaks into shaly fragments. The sandstone over this ash bed contains fish-scale impressions, and 100 feet beneath it is a sandstone bed which generally holds pebbles of a black chert. * * * West and south of the Highwood Mountains it [the Benton] consists of dark-gray or black shales in beds 50 to 200 feet thick, alternating with yellowish, rather massively bedded sandstones. * * *

Eagle formation.—The Eagle formation * * * consists of a sequence whose most prominent bed is sandstone. The whiteness of the formation is in marked contrast to the dark-gray shales above and below it. The formation consists at the base of thinly laminated sandstones stained light brown by lignitic material and containing concretions and nodular masses of iron ore. These beds grade upward into a pure white sandstone which * * * forms extensive bluffs 75 to 100 feet high. * * * Exposures * * * occur in the bluffs of Arrow Creek and northeast of Square Butte, where its thickness is 235 feet. At these localities the beds are nearly level or but slightly tilted and their relation to the leaden-gray Colorado shales beneath is clearly seen. * * * Fresh-water shells are found in white sandstone beds in the Highwoods [a] which may represent the formation, but the strata are flexed and disturbed, while the species identified are forms commonly found in the Laramie. The beds on Arrow Creek are clearly capped by a conformable series of marine beds 2,000 feet in thickness, which are in turn overlain by the Laramie to the east (of the map).

Montana formation.—The Montana formation is composed principally of leaden-gray clay shales which are much like those of the underlying Colorado. The formation contains much sandstone interbedded with the shales in the Highwood Mountains. * * * The subdivisions of the Montana recognized farther east are not found here, and it is doubtful whether the top of the formation exists within the limits of the Fort Benton quadrangle.[b]

Summary.—On top of these formations are bench gravels and alluvium in the stream bottoms, and over a part of the area outside of the foothill country there is spread the continental glacial drift and till, carrying bowlders from distant sources. The total thickness of the sediments in this area, as given by Mr. Weed, is as follows:

Thickness of sedimentary rocks near Highwood Mountains.

Surficial materials	variable.
Montana	1,200–1,600
Eagle	235
Colorado	1,850
Dakota	180
Cascade	500

This gives a total thickness of from 4,000 to 4,500 feet of soft sandstones and shales of the character described above. These strata are weak, unresistant, and easily ruptured, and without doubt this fact has had great influence in determining the character of the intrusions and the great number of dikes which in the Highwoods form so marked a feature of the structural geology. Except for local disturbances in the mountains, the beds are horizontal or nearly so.

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[a] That is, in the mountain area itself.—L. V. P.

[b] Consequently it is not found in the area shown on the accompanying geologic map (Pl. III).—L. V. P.

CHAPTER VI.

PETROGRAPHY.

INTRODUCTION.

The Highwood Mountains have proved a very interesting field for the petrographer. Some of the rock types that they have furnished have proved of importance in systematic petrography, and all of them are more or less novel in character and their study and description has added to the theoretic side of the science. Rosenbusch[a] early called attention to the importance of the igneous rocks of central Montana, and in concluding his brief report upon the Highwoods in 1885 Lindgren says: "Future examination will doubtless reveal rich harvests to the petrographer in the Highwoods and in the mountains of the upper Musselshell River." The truth of this remark has been shown in his own paper on the syenite of Square Butte and the various memoirs on this region published by Mr. Weed and the writer, and it will receive, we believe, a further illustration in the present work.

The field can not be considered, however, as exhausted. The expenditure of the amount of time necessary to make complete collections for petrographic purposes would not have been warranted under the circumstances by the results to be attained. Without doubt, in the future, petrographers will find many matters of interest which were overlooked or only touched upon in the necessarily rapid field work. It is believed that the larger features of importance which the district affords and which tend to the elucidation of the many problems of petrology that confront the student of igneous rocks have been discovered and are sufficiently treated in the present work.

Most of the analyses here given have been already published in Bulletin No. 228 of the United States Geological Survey, with very brief notes or lists of their minerals and under the provisional field names first used by the author. Those who have used the analyses will find no difficulty in recognizing them in the present work.

Summary of Lindgren's petrographic work.—Lindgren[b] regarded the Highwoods as the basement complex of an old volcano whose pipes and dikes had resisted erosion and given form to the moun-

[a] Mikr. Phys. Mass. Gesteine, 3d ed., 1895, p. 128.

[b] Tenth Census, vol. 13, pt. 15, Mining Industries, 1885, pp. 724–730.

tains. In describing the rocks petrographically he divides them into trachytes and basalts. Since they are considered post-Cretaceous in age he does not directly classify them as syenites and other granular rocks, but, following the prevailing usage of that time, he placed them under the headings mentioned above, and considered the granular types he met as the equivalents of syenite, etc. It should be recalled that at that time the age distinction with respect to igneous rocks still held a strong position with the leading systematists.

Under the trachytes three types are described: (*a*) Coarse granular, (*b*) porphyritic with feldspathic groundmass, and (*c*) porphyritic with a strongly augitic groundmass. The first type, so far as one can judge, seems founded on the syenite (pulaskose) of Highwood Peak. The second is clearly a description of the highwoodose (tinguaite var. highwoodite) of the great dike, about 1 mile north of Highwood Gap, in the valley bottom. The augite he describes rather fully, and considers it to be the same throughout the whole range of Highwood rocks. A series of specimens are then briefly described, in which there is a gradual increase in the ferromagnesian components, especially the augite, until they become dark basaltic types or basalts with sanidine instead of plagioclase. The appearance of olivine in these is noted. This progression brings us to the third type, with strongly augitic glassy groundmass. These are dense dark-green or gray rocks, with phenocrysts of augite, feldspar, and nosean (or analcite), and isotropic groundmass full of augite needles. Of these types just mentioned no locality is given, but from the general course of the party through Highwood Gap they appear to have been collected in this part of the mountains, and would seem to be some of the basaltic dikes of this part of the area. The last type appears to be a rock of tinguoid habit, judging from Lindgren's description and his correlation of it with a Judith Mountains type, where rocks of tinguoid appearance (judithose) are common, as described by the writer. In this case it can be referred to the tinguaite (pulaskose) of South Peak, as described later.

Lindgren's account of the Highwood rocks is concluded by a rather full description of the analcite-basalts, the first announcement of this interesting group. This was followed by a later paper dealing especially with them and discussing the origin of the analcite, which is held to be of primary origin. This part of his work on the Highwood rocks will be referred to in detail later, when the analcite rocks are discussed.

Previous work of the author.—As mentioned in the bibliography of the Highwoods, several papers dealing with particular phases of the rocks or descriptive of special types have been published by the writer, with field notes upon the occurrences by Mr. Weed. In this report that material has been drawn upon so far as is necessary to give completeness to the work, and the results of additional study and correlation will be added.

CLASSIFICATION.

For purposes of petrographic description the Highwood rocks will be classified according to their geologic mode of occurrence. It is admitted at the outset that this represents no scientific system of classification, since by it things quite diverse in a petrographic sense might be brought together. Under the head of dikes, for instance, might be included rocks of all kinds mineralogically and rocks of granular, porphyritic, and even glassy texture. The classification is made solely for convenience in local use and reference. According to this classification, the rocks will be divided into the rocks of the stocks, of the laccoliths, of the dikes and sheets, and of the extrusive flows and breccias. They are named and described according to the new system of classification devised by the author and others,[a] and it is hoped that the work will serve as an illustration of the use of this system. According to it, the following classes, orders, rangs, and subrangs are represented in the Highwood Mountains:

Rocks represented in Highwood Mountains, according to new classification.

Class.	Order.	Rang.	Subrang.
Persalane	Canadare	Pulaskase	Pulaskose.
Dosalane	Austrare	Dacase	Adamellose.
	Germanare	Umptekase	Highwoodose.
		Monzonase	Monzonose.
		Andase	Shoshonose.
	Norgare	Laurdalase	Fergusose.
		Essexase	Borolanose.
Salfemane	Fortugare	Wyomingase	Montanose.
		Monchiquase	Shonkinose.
			Monchiquose.
	Kamerunare	Kamerunase	Cascadose.
	Bohemare	Albanase	Albanose.

To one acquainted with the new system and its precise definition of magma units this assemblage of subrangs gives a general idea of Highwood magmas and rocks and their genetic relations with one another that it would be difficult to convey except by long descriptions.

Since this new system is as yet hardly old enough for petrographers to have become thoroughly acquainted with it, the rocks in the following descriptions are also given the usual names; the reader will thus be able to make comparisons between the systems and to correlate the

[a] Cross, Iddings, Pirsson, and Washington, Quantitative Classification of Igneous Rocks, Chicago, 1903.

types with those of other regions. According to the prevailing systems the rocks to be described are as follows:

Rocks represented in Highwood Mountains, according to prevailing classification.

GRANULAR ROCKS.

Syenite, Augite (Albany type of Rosenbusch). Highwood Peak.
Syenite, Augite (basic type approaching shonkinite). Middle Peak.
Syenite, Sodalite. Laccoliths.
Syenite, Nosean (new type). Intrusive near Highwood Gap.
Monzonite. Highwood Peak.
Shonkinite. Shonkin stock and the laccoliths.
Shonkinite (with leucite). East Peak and Shonkin stock.
Missourite. Shonkin stock.
Fergusite (new type of leucite rock). Arnoux stock.

PORPHYRITIC ROCKS.

Syenite-porphyry (Highwood type). In dikes.
Trachyte-porphyry (hornblende-bostonite-porphyry?). In dikes.
Tinguaite-porphyry (Highwood type). In dikes.
Trachyandesite (latite). In flows and breccia.
Minette (Highwood type). In dikes and sheets.
Analcite-basalt (monchiquite). In dikes and flows.
Pseudoleucite-basalt. In dikes, sheets, and flows.

PETROGRAPHY OF STOCKS AND LACCOLITHS

GRANO-PULASKOSE (SYENITE VAR. PULASKITE) OF HIGHWOOD PEAK.

A light-colored feldspathic rock composes the southern half of Highwood Peak in its upper portion and extends in talus slides and outcrops down to the southwest. It has a jointing which produces large, heavy slabs several feet long and a foot or more in thickness, which are best seen on the summit of the peak, where they occur in the rather massive outcrops. At this point the rock is very light colored, almost white, with a pinkish to pale brownish tinge. Lower down on the southwest in the gulches and southward on the divide the color changes to a light smoke gray.

Megascopic characters.—In the hand specimen the white rock from the top is clearly seen to be almost wholly composed of feldspar having a tabular development, which gives the rock a trachytic habit. This is not so noticeable in the gray variety, which is more granitoid in character. Both varieties are dotted somewhat sparsely with ferromagnesian minerals, pale-green diopside, or glittering biotite in small crystals. In the rock at the top these minerals are in many places dull and lusterless or changed to little masses of limonite. The feldspar tables, which are the chief components, give cross sections which average about 8 mm. in length by about 2 mm. in breadth, and show the granularity of the rock. In the gray variety they are not so long and the fabric is more like that of a common granite.

Microscopic characters.—Under the microscope there are seen in the sections the following minerals: Iron ore, titanite, apatite, diopside, hornblende, biotité, alkali feldspars, quartz, and secondary muscovite, kaolin, calcite, and chlorite.

Iron ore in small formless grains is rather uncommon and occurs usually with the diopside. The titanite and apatite are also rare. They occur generally in small masses, the apatite having the form of short prismoids.

The diopside is partly in small stout prisms, partly in very small scattered grains, and has a clear, very pale-green color without pleochroism. It has a well-marked but not perfect prismatic cleavage and a wide extinction angle, approaching 45°. The computation of the rock analysis given beyond (p. 63) shows its approximate composition to be that given below.

An analysis of a pyroxene from Edenville, N. Y., by Hawes[a] is quoted for comparison:

Composition of diopside from Highwood Peak and pyroxene from Edenville, N. Y.

	I.	II.
SiO_2	52.8	51.05
Al_2O_3		2.02
Fe_2O_3		1.30
FeO	10.2	12.28
MnO		.12
MgO	12.4	10.02
CaO	24.6	22.07
Ignition		.34
Total	100.0	99.10

I. Diopside from Highwood Peak.
II. Pyroxene from Edenville, N. Y.; analysis by Hawes.

This is placed at the end of the diopside group by Dana.[b] The proportion of the different molecules is $12MgCaSi_2O_6$ to $5FeCaSi_2O_6$, and it therefore clearly belongs to the diopsides rather than to the hedenbergite group.

The diopside is altered in many places to a fibrous green hornblende, and the latter is also occasionally found alone; but unaltered cores of the diopside remaining in many of the bundles of hornblende

[a] Am. Jour. Sci., 2d ser., vol. 16, 1878, p. 397.
[b] System Mineralogy, 6th ed., p. 359.

show the original mineral. The hornblende does not appear to be anywhere original.

An ordinary brown biotite is present in small amount. It is more abundant in the rock forming the lower southern slopes of the peak than at the top, and is often bleached or changed to a chlorite.

Of the dark-colored minerals the diopside is by far the most abundant, the others in comparison being limited in amount. In some areas these ferromagnesian components are partly changed to chlorite.

The feldspars are all alkalic, as proved by their optical properties and by the study of the analysis, which shows all the lime demanded for the diopside. They are developed tabular on m (010), and the cleavage parallel to c (001) is very pronounced. Between crossed nicols they are very nonhomogeneous; are watered, waved, or moiré in appearance; have perthite bands and included masses of a somewhat higher birefringence, and these areas and masses pass in spots into albite with distinct albite twinning. In some specimens it is difficult to find an area which appears really homogeneous, but in such a section normal to the obtuse positive bisectrix, and hence approximately parallel to b (010), the direction of extinction $\mathfrak{a}$ is 13° from the trace of the good basal cleavage (001) on b (010) and lies in the positive obtuse angle β. Hence the feldspar is a soda orthoclase, and the large extinction angle would, in a general way, indicate a high content of soda. This is confirmed by the analysis, which shows that in general the feldspar content is in the proportion of Or_1Ab_2.

While in some specimens the feldspar is fresh and clear, in others it is muddy and clouded with kaolin leaves, and when this occurs the nonhomogeneous aspect disappears, though whether this is merely an accident or there is some relation by which the more homogeneous feldspar suffers this change more easily could not be determined.

White mica is present in the rock from the top of the peak. This is seemingly of secondary origin, in part after biotite, in which case it is in large crystals, and in part after feldspar, when it is in small nests and rosettes in the feldspar. Its amount at times may be considerable.

In the rock at the top some quartz occurs filling fine angular interspaces between the feldspars. In the grayish variety along the south slopes it disappears, and the specimens taken here were tested chemically to ascertain if a small amount of nephelite might not be present, but without result. In one section an area of calcite was observed filling an angular interspace between feldspars in the same manner that Hawes[a] observed in the hornblende-syenite from Columbia, N. H. This is probably, as Rosenbusch[b] remarks, a product of infiltration into miarolitic cavities in the rock. The texture of the syenite lends additional confirmation of this idea.

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[a] Geol. and Lithol. New Hampshire, 1878, p. 208.

[b] Mikr. Phys., Mass. Gesetine, 3d ed., 1895, p. 56.

Chemical composition.—The chemical composition of the rock is shown by the first analysis in the following table:

Analyses of pulaskose of Highwood Peak and related rocks.

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.
SiO_2	65.54	65.43	66.60	66.13	60.03	64.64	68.34	1.092
Al_2O_3	17.81	16.11	15.05	17.40	20.76	16.27	15.32	.173
Fe_2O_3	.74	1.15	1.07	2.19	4.01	2.42	1.90	.005
FeO	1.15	2.85	4.42		.75	1.58	.84	.016
MgO	.98	.40	.36	.04	.80	1.27	.54	.024
CaO	1.92	1.49	2.21	.81	2.62	2.65	.92	.034
Na_2O	5.55	5.00	4.03	5.28	5.96	4.39	5.45	.089
K_2O	5.58	5.97	5.42	5.60	5.48	4.98	5.62	.059
$H_2O+110°$	.54	.39	.41	1.22	.59	.27	.30	.030
$H_2O-110°$		.19				.09	.15	
TiO_2	.11	.50	.76	.74	(?)	.51	.21	.001
P_2O_5	Trace.	.13	--------	(?)	.07	.37	.13	--------
CO_2	Trace.	Trace.	--------	--------	--------	.37	--------	--------
F	--------	.08	--------	--------	--------	--------	--------	--------
Cl	--------	.05	--------	--------	--------	.05	.04	--------
ZrO_2	--------	.11	--------	--------	--------	--------	--------	--------
MnO	Trace.	.23	Trace.	.13	Trace.	Trace.	.07	--------
SrO	--------	--------	--------	--------	(?)	.08	.04	--------
BaO	(?)	.03	None.	(?)	(?)	.18	.08	--------
Li_2O	--------	--------	--------	--------	(?)	--------	None.	--------
FeS_2	--------	.07	--------	--------	--------	--------	--------	--------
Total	99.92	100.18	100.33	99.54	101.07	100.12	99.95	--------

I. Pulaskose (syenite) from top of Highwood Peak. Highwood Mountains, Montana. L. V. Pirsson and W. L. Mitchell, analysts.

II. Phlegrose (syenite) from Mount Ascutney, Vermont. W. F. Hillebrand, analyst. Bull. U. S. Geol. Survey No. 148, p. 68.

III. Toscanose (syenite, akerite) from Prospect street, Gloucester, Mass. H. S. Washington, analyst. Jour. Geol., vol. 6, 1898, p. 798.

IV. Phlegrose (syenite, porphyritic akerite) from between Thinghoud and Fjelebua, Norway. Mauzelius, analyst. Brögger, Zeit. Kryst., vol. 16, 1890, p. 46.

V. Pulaskose (pulaskite) from Fourche Mountain, Arkansas. R. N. Brackett and J. P. Smith, analysts. Ann. Rept. Geol. Survey Arkansas for 1890, vol. 2, p. 70.

VI. Toscanose (syenite) from Hughsville, near Barker, Mont. W. F. Hillebrand, analyst. Twentieth Ann. Rept. U. S. Geol. Survey, pt. 3, p. 19.

VII. Liparose (quartzose syenite) from head of Beaver Creek, Bearpaw Mountains, Montana. H. N. Stokes, analyst. Am. Jour. Sci., 4th series, vol. 1, 1896, p. 354.

VIII. Molecular ratios of No. I.

In the prevailing systems of classifications this rock is a typical syenite in which the silica reaches the upper limit of the group and the rock stands next to the granites. The alumina and alkalies are high, the ferromagnesian elements low, and the rock is therefore in the alkaline series of syenites. A number of analyses of similar rocks from other parts of the world are introduced for comparison, and attention will be drawn to some of them later.

Mineral composition or mode.—By considering the molecular ratios given in column VIII of the table of analyses and the minerals disclosed by the section, the rock may be shown to have the following mineral composition by weight:

Mineral composition or mode of pulaskose of Highwood Peak.

	Iron ore.	Pyroxene.	Orthoclase.	Muscovite.	Albite.	Quartz.	Calculated.	Found.
SiO_2		4.08	15.84	5.40	32.04	8.16	65.52	65.54
Al_2O_3			4.53	4.63	9.17		18.33	17.81
Fe_2O_3	0.74						.74	.74
FeO	.36	.72					1.08	1.15
MgO		.98					.98	.98
CaO		1.92					1.92	1.92
Na_2O					5.55		5.55	5.55
K_2O			4.15	1.41			5.56	5.58
H_2O				.54			.54	.54
Total	1.10	7.70	24.52	11.98	46.76	8.16	100.22	99.81

The occasional biotite crystals and the small amount of hornblende may be considered with the pyroxene. All of the water has been assigned to the muscovite, whereas undoubtedly a part is hygroscopic. This makes the amount of muscovite somewhat too high, and also tends to lower the orthoclase. With these exceptions the calculation represents the composition of the rock very closely. That there is only 9 per cent of normative femic constituents in the mode shows the strong salic character of the rock.

Classification in the new system.—From the analysis of the rock previously given, its position in the new system of classification may be determined by calculation of the norm, as shown in the following table:

Calculation of norm of pulaskose of Highwood Peak.

	Analysis.	Molecular ratios	Or.	Ab.	An.	Qz.	Di.	Hy.	Mt.	Il.
SiO_2	65.54	1.092	354	534	50	111	18	25		
Al_2O_3	17.81	.173	59	89	25					
Fe_2O_3	.74	.005							5	
FeO	1.15	.016					3	7	5	1
MgO	.98	.024					6	18		
CaO	1.92	.034			25		9			
Na_2O	5.55	.089		89						
K_2O	5.58	.059	59							
TiO_2	.11	.001								1
H_2O	.54									
Total	99.92		59	89	25	111	9	25	5	1

Or	32.80	93.04
Ab	46.63	
An	6.95	
Qz	6.66	
Di	2.04	6.07
Hy	2.72	
Mt	1.16	
Il	.15	
H_2O	.54	
Total	99.65	

Class, $\frac{\text{Sal.}}{\text{Fem.}}=\frac{93.04}{6.07}=15.3$=I, persalane.

Order, $\frac{Q}{F}=\frac{6.66}{86.38}=.077$=perfelic=5, canadare.

Rang, $\frac{K_2O'+Na_2O}{CaO'}=\frac{148}{25}=5.8$=domalkalic=2, pulaskase.

Subrang, $\frac{K_2O'}{Na_2O'}=\frac{89}{59}=1.5$=sodipotassic=pulaskose.

Since the texture of the rock has been shown to be the broad trachytic one, it may thus be termed a tracho-pulaskose, which, as the fabric varies into the granitic, passes locally into grano-pulaskose.

Classification in prevailing systems.—If account be taken of the tendency of the lighter colored feldspars to assume a tabular habit, giving the somewhat broadly trachytoid texture, and of the paucity of dark minerals, the rock belongs to the pulaskite type of syenites of Rosenbusch. It does not differ markedly from the pulaskite of Arkansas, whose analysis is given in the table on page 63, except in regard to silica and alumina. It might with propriety be termed a pulaskite type of syenite with accessory quartz.

The gray variety does not show this tendency to the trachytoid structure, but is purely granitoid in type. It appears more nearly related to the akerites than to any other type of syenite given by Rosenbusch. It agrees very closely with the akerite in chemical composition, as is shown by the analyses on page 63. In whatever way it may be classified it clearly belongs in the alkaline series of syenites, which passes from the alkali-granites on the one hand and grades into the foyaite or nepheline-syenite group on the other.

PULASKOSE (SODALITE-SYENITE) OF SQUARE BUTTE.

Introductory.—This rock was very fully described by Lindgren, with analyses by Melville of material collected by Dr. C. A. White, and was mentioned in the former paper by Mr. Weed and the writer. It has become well known in the literature of petrography, and here only such details will be given as are necessary to complete the discussion of the petrography of the region and of the position of the rock in the new system of classification.

Megascopic characters.—On fresh surfaces the rock is white, often with a pale-brown or pinkish tinge. It has a very heavy jointing, and on top of the butte it often appears in huge, thick slabs several yards long. It is made up mostly of feldspars, which have lath-like or tabular forms and reach 5 mm. in length. Through it are freely sprinkled slender, black, glittering prisms of hornblende of about the same average length as the feldspar. There is not enough hornblende to detract from the light color of the rock at a distance. Small grains of a salmon or pale-brown colored sodalite are also present.

Texture.—The platy form of the feldspars gives the rock a broad trachytoid texture—that which in the nephelite-syenite characterizes the "foyaite" type of Brögger. Since the interspaces between the feldspars are not always completely filled, the rock has a more or less miarolitic habit.

Microscopic characters.—The microscope shows the following minerals present, mentioned in the order of their formation: Apatite, hornblende, orthoclase and albite, sodalite, nephelite, and analcite.

The hornblende has its prisms bounded by m (110) and b (010); terminations are wanting. It is frequently twinned on a (100). It is strongly pleochroic, $\mathfrak{c}$ and $\mathfrak{b}$ deep chestnut brown, $\mathfrak{a}$ yellowish brown, and absorption strong; $\mathfrak{b}=\mathfrak{c}>\mathfrak{a}$. In the outer margins it is often changed to a deep greenish color, the brown merging into the green. The angle of $c \wedge \mathfrak{c}$ is 13°. It is automorphic against the feldspathic components. A few of the hornblendes contain iron-ore grains, but these do not occur in the rock except as inclusions of this character. The hornblende is similar to the brown hornblende found in the nephelite-syenite of Red Hill and other alkalic rocks, and is near barkevikite in composition, as shown by the following analysis by Melville:

Analysis of hornblende of sodalite-syenite of Square Butte.

SiO_2	38.41
TiO_2	1.26
Al_2O_3	16.39
Fe_2O_3	3.75
FeO	21.75
MgO	2.54
MnO	.15
CaO	10.52
Na_2O	2.95
K_2O	1.95
H_2O	.24
Total	99.91

The marked feature of this hornblende is the large amount of alumina and iron it contains.

The alkali feldspars are chiefly orthoclase in lath-shaped sections, and associated with them is a certain amount of a triclinic feldspar shown to be albite. In the interstices between them is the colorless isotropic sodalite, and the study of sections from different portions of the mass shows that in addition to this component there is present a variable amount of nephelite, which in some cases is abundant and in others is nearly or wholly wanting. In Lindgren's material there was also considerable analcite, and this occurs generally. So far as can be told, the analcite appears to be wholly secondary, in part after nephelite and in part after feldspar; in the latter case it occupies bays, tongues, and areas eaten into the feldspar. The sodalite is at times partly or wholly replaced by cancrinite, and in other cases bundles of fibrous natrolite occupy angular interspaces and, judging by the manner of occurrence, are secondary after sodalite or nephelite. The sodalite and analcite were separated and analyzed by Melville, with the results given in the table on the next page.

Mineral composition or mode.—From the bulk analysis of the rock given below, and from those of its components, Lindgren calculated that its mineral composition is as follows:

Mineral composition of pulaskose of Square Butte.

Hornblende	23.00
Orthoclase	50.00
Albite	16.00
Sodalite	7.96
Analcite	3.03
Total	99.99

These results would be modified somewhat if the material studied had contained the unchanged nephelite. Lindgren remarks that the sodalite may contain some hydroxyl. The amount present is calculated at practically 8 per cent. The rock contains 0.43 per cent of chlorine, which would give 5.4 per cent in the mineral. In theory normal sodalite requires 7.3 per cent.

Chemical composition.—In the following table are analyses of this rock and of its mineral components, by Melville. An analysis of a related rock is added for comparison.

Analysis of pulaskose of Square Butte and component minerals.

	I.	II.	III.	IV.	V.	VI.	VII.
SiO_2	56.45	0.941	38.41	0.640	41.56	49.54	49.06
Al_2O_3	20.08	.197	16.39	.161	29.48	25.07	16.07
Fe_2O_3	1.31	.008	3.75	.023			7.92
FeO	4.39	.061	21.75	.302	.49	.40	2.41
MgO	.63	.015	2.54	.063	.15	.20	2.65
CaO	2.14	.038	10.52	.188	.49	.22	8.21
Na_2O	5.61	.090	2.95	.048	19.21	15.32	5.17
K_2O	7.13	.076	1.95	.021	.91	.89	3.18
H_2O+	1.77		.24		3.73	7.49	2.27
H_2O-					.45		
CO_2							1.21
TiO_2	.29	.004	1.26	.016			.81
P_2O_5	.13	.001					.61
SO_3							Trace.
Cl	.43	.012			4.79	1.67	Trace.
MnO	.09		.15				.98
	100.45		99.91		101.26	100.42	100.55
O=Cl	.10				1.08	.42	
	100.35				100.18	100.00	

I. Pulaskose (sodalite-syenite) from Square Butte. W. H. Melville, analyst.
II. Molecular ratio of I.
III. Barkevikite from above. W. H. Melville, analyst.
IV. Molecular ratio of III.
V. Sodalite with some analcite from above. W. H. Melville, analyst.
VI. Analcite with some sodalite from above. W. H. Melville, analyst.
VII. "Sodalite-syenite" from Schlossberg, near Grosspriesen, Bohemia. F. Hanusch, analyst. Hibsch, Tscher. Min. Pet. Mitt., vol. 21, 1902, p. 522.

Since hornblende is the only ferromagnesian mineral in the rock, it contains all the iron, magnesia, and titanic acid. The feldspars appear purely alkalic, and if so the lime is also all in the hornblende. In this case the ratio of the oxides to one another should be the same in the hornblende analysis as in the rock analysis. These ratios are as follows:

Oxides in hornblende and pulaskose of Square Butte.

	Hornblende.	Pulaskose.	Ratio.
Fe_2O_3	3.75	1.31	2.86
FeO	21.75	4.39	4.95
MgO	2.54	.63	4.03
CaO	10.52	2.14	4.91
TiO_2	1.26	.29	4.03

The titanic acid in the hornblende was calculated from the rock analysis and can not, therefore, be taken into account. The amount of magnesia in the rock is so small that the ordinary variations of analytical work might render this ratio not very exact. The ferrous irons and the limes show close agreement, based on larger quantities, but if they are correct the ferric irons can not be. Taking everything into account, it seems probable that in either the rock or the hornblende the amount of ferrous to ferric iron has not been very correctly determined, and that the error is in the rock determination, which should be about 0.86.

Classification in prevailing systems.—This rock has been called a sodalite-syenite, and Rosenbusch, mindful of the rather small amount of feldspathoids present, has placed it under the alkaline syenites rather than in the nephelite-syenite family proper. Under this system of classification, especially if the variable nephelite and sodalite is considered, the rock forms a connecting link between the two families.

Classification in the new system.—In the new system of classification the position of the rock is seen in the next table, in which its norm is calculated from the chemical analysis. It is of interest to note that this gives 70.56 per cent of alkalic feldspar, while Lindgren's calculation gives 66 per cent, the difference arising in the 3 per cent of analcite in his calculation. The 23 per cent of hornblende of the mode is replaced by anorthite, olivine, and iron ores in the norm, making all told 18.11 per cent, the difference being due to the fact that no femic alkalic constituents appear. This furnishes an excellent example of how the same oxides may be shifted to produce quite different mineral molecules, so that under a given set of conditions the oxides forming the usual component minerals may be united to form a single constituent differing in character from all of them.

Calculation of the norm of pulaskose of Square Butte.

	Analysis.	Molecular ratio.	Or.	Ab.	An.	Ne.	So.	Co.	Ol.	Mt.	Il.	Ap.
SiO_2	56.45	0.941	0.456	324	70	24	36		31			
Al_2O_3	20.08	.197	76	54	35	12	18	2				
Fe_2O_3	1.31	.008								8		
FeO	4.39	.061							49	8	4	
MgO	.63	.015							13			
CaO	2.14	.038			35							3
Na_2O	5.61	.090		54		12	24					
K_2O	7.13	.076	76									
TiO_2	.29	.004									4	
P_2O_5	.13	.001										1
Cl	.43	.012					6					
Rest	1.29											
Total	100.35		76	54	35	12	6	2	31	8	4	1

Or	42.26	89.86
Ab	28.30	
An	9.73	
Ne	3.41	
So	5.96	
Co	.20	
Ol	5.91	8.72
Mt	1.86	
Il	.61	
Ap	.34	
Rest	1.29	
Total	99.87	

Class, $\frac{\text{Sal.}}{\text{Fem.}}=\frac{89.86}{8.72}=11.3=\text{I}$, persalane.

Order, $\frac{\text{L.}}{\text{F.}}=\frac{9.37}{80.31}=0.11=$perfelic$=5$, canadare.

Rang, $\frac{K_2O'+Na_2O'}{CaO'}=\frac{166}{35}=4.7=$domalkalic$=5$, pulaskase.

Subrang, $\frac{K_2O'}{Na_2O}=\frac{90}{76}=1.2=$sodipotassic$=$pulaskose.

Comparison with related types.—When it was believed that this rock contained sodalite as its only feldspathoid (lenad component) it stood in a class largely by itself. The fact that it contains nephelite, however, renders it akin to the other alkali-feldspar rocks which contain small amounts of this mineral. It is thus closely allied with the brown hornblende-bearing rock of Red Hill, described by Bayley,[a] which contains a rather limited amount of nephelite and some sodalite. In the very able and valuable memoirs of Hibsch upon the interesting rocks of the Bohemian Mittelgebirge, brought out in recent years, he describes a "sodalite-syenite," the analysis of which is given for comparison. The similarity, however, ends with the sodalite, since its composition, as shown by Hibsch, is the same as that of the essexite of the Rongstock, and it appears indeed questionable if in any system of classification which takes account of the relative quantities of the minerals, rocks so rich in ferromagnesian components should be classed with the feldspathic syenites.

[a] Bull. Geol. Soc. America, vol. 3, 1892, p. 231.

TRACHO-HIGHWOODOSE (NOSEAN-SYENITE).

Occurrence.—This rock occurs as a dike or small intrusive mass in the Cretaceous strata south and somewhat east of South Peak, in the foothills and between two small head branches of Byrnes Creek. With the small scale and somewhat generalized character of this portion of the map, it is impossible to locate it more definitely. On the day it was discovered the country was covered with dense smoke from forest fires, which made it impossible to take bearings by which its position could be accurately given, and the necessities of the work did not permit of a second visit to this locality.

Megascopic characters.—The weathered rock is a light brownish gray and has a somewhat cellular structure, owing to the relief caused by tabular feldspars arranged in trachytoid texture which have resisted weathering better than the other elements. Such sections attain lengths of from 2 to 5 mm.

On a freshly fractured surface the rock has a clear gray color with something of an olive tone, and the individual constituents are not very clearly contrasted. With the lens it is seen that the white feldspars are dotted through and through with tiny dark-green specks and prisms of a ferromagnesian mineral, while the interspaces between them are filled with a much larger proportion of ferromagnesian grains. An occasional flake of biotite is also seen.

Under the microscope the following minerals are seen: Iron ore, apatite, titanite, pyroxene, biotite, alkali feldspar, nosean, kaolin, and probably analcite.

Microscopic characters.—The iron ore is in small octahedrons, and is rather sparing in amount. Apatite, which is rare, is in short, thick prisms. Biotite is strongly pleochroic and shows slight peculiarities which recall its characters in the minettes; the outer border is deeper colored than the interior, and the crystal form is embayed or repeated. It is a comparatively rare component, as is also titanite, of which a few scattered crystals were seen.

The pyroxene shows considerable diversity of character; it is usually present in slender prisms which reach a maximum length of 2 mm. In a few cases short, stout columns were noted. The larger crystals are composed of a pale-green diopside with high extinction angle and strong birefringence. Toward the periphery they assume a darker green from admixture of the ægirite molecule, and are here a transition between ægirite-augite and diopside. Their outline is very apt to be beaded in the section by small attached grains of iron ore. In some places they are changed into a yellowish serpentine substance. In a few cases, especially in the vicinity of nosean, the augites become much richer in ægirite and pass over into ægirite-augite. The smaller microlites are much more apt to be darker colored, and in some cases, especially in the interspaces enriched in soda, they pass over into ægirite, or if of diopside the end projecting into the nosean is of ægirite. This is similar to the occurrence of such pyroxenes in the phonolite of Cripple Creek as described by Cross[a] and in the analcite-basalt of the Little Belt Mountains described by the writer.[b] These small pyroxenes are neither numerous enough nor small enough to give the tinguaitic aspect, but in some of the interspaces they are rather thickly crowded. A somewhat similar structure of a syenite rock with thickly scattered small diopside prisms has been described by the writer from the Little Belt Mountains, Montana.[c]

The orthoclase feldspar which makes up over half of the rock is in tabular crystals that produce the trachytoid structure so common in the alkalic rocks. It is somewhat kaolinized in places. It contains also at times the albite molecule by means of which it passes into soda orthoclase, or it may contain microperthite intergrowths with albite. The size of these feldspar tables as seen in the section is about 2 mm. long by 1 mm. broad.

In the angular interspaces between these feldspars there is a clear colorless isotropic mineral of low refractive index. This is generally sprinkled through with the pyroxene microlites previously mentioned. It does not show any other positive characters by which it might be identified, and might be taken for glass if the character of the rock and its mode of occurrence did not utterly preclude such an idea.

Chemical composition.—At first this substance was believed to be analcite, like that of the analcite-syenite from the neighboring Little Belt Mountains[d], but when treated with dilute nitric acid the powdered rock gelatinized readily, and the acid solution after being filtered gave a strong reaction for sulphuric anhydride SO_3 and a mere trace of chlorine. Carefully treated with very dilute hydrochloric acid, the test for SO_3 gave the same result. The SO_3 did not come, therefore, from oxidation of metallic sulphides, but from a soluble sulphate. The powdered rock gives but little water in the closed tube. The chemical tests show that a considerable amount of nosean must be present in the rock, and it must be a part of the colorless isotropic substance. Some analcite is probably present, and is perhaps indicated in places where the isotropic substance is particularly clear and limpid. In such spots a rough cubic cleavage can be seen, and at times faint optical anomalies. Here, also, some particles of calcite are found, in one case with distinct crystal form. It seems probable that the analcite is secondary after the nosean. A test by the method

[a] Geology of the Cripple Creek district: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 2, p. 35.

[b] Petrography of the Little Belt Mountains: Twentieth Ann. Rept. U. S. Geol. Survey, pt. 3, p. 546.

[c] Ibid., p. 468 (No. 643).

[d] Ibid., p. 469.

recommended by Osann[a] for distinguishing nosean from other minerals of the feldspathoid group, by using acetic acid and barium chloride on the section, was partly successful; some areas had $BaSO_4$ deposited upon them, while others remained clear.

No complete chemical analysis of the rock was undertaken, as it did not appear fresh enough to warrant the labor, but a partial one

Actual mineral composition or mode of tracho-highwoodose from near South Peak.

Units measured.		Volume, per cent.		Specific gravity.				Weight, per cent.
Or	819	58.93	×	2.6	=	153.2	=	53.6 orthoclase, albite.
No	100	7.20	×	2.2	=	15.8	=	5.5 nosean.
Di	329	23.67	×	3.3	=	78.1	=	27.3 diopside.
Ac	28	2.01	×	3.5	=	7.0	=	2.3 ægirite.
Bi	12	.86	×	3.0	=	2.6	=	.9 biotite.
Mt	50	3.60	×	5.2	=	18.7	=	6.4 magnetite.
Ap	25	1.79	×	3.2	=	5.7	=	2.0 apatite.
Cc	14	1.00	×	2.7	=	2.7	=	.9 calcite.
Tn	13	.94	×	3.3	=	3.1	=	1.1 titanite.
Total	1,390	100.00				286.9		100.0

by Dr. W. F. Hillebrand will be given later. However, the rock appears to be a fair subject for microscopic analysis by Rosiwal's method, and this was undertaken, with the above results. Under ægirite is understood those pyroxenes which were deep green and pleochroic. Chance brought several titanites in the measured lines, and the amount may be rather high. To reduce this to a chemical composition it is arbitrarily assumed that at least 10 per cent of albite is present, the biotite is divided into 5 parts of leucite and 4 of olivine, the pyroxenes are united, and their mass composition assumed to be that of a very similar one from the soda granite of Kekekabic Lake,[b] whose composition is known. Making these assumptions, the chemical composition may be figured from the mineral analysis given in the above table. The titanic acid appears rather high, and there is probably a more even relation in the iron oxides. The computed analysis is reckoned, of course, on a water-free basis. That it represents closely the composition of the rock is evident from its agreement, first, with the partial analysis by Doctor Hillebrand and, second, with the chemical analyses of closely related rocks of the area. These facts may be seen in the table on the next page, where all the analyses are given with water and traces omitted:

[a] Neues Jahrb. für Min., 1892, vol. 1, p. 222.
[b] Am. Geol., vol. 11, 1893, p. 385.

Chemical composition of highwoodose calculated from mode.

	Or.	Ab.	Lc.	No.	Di.	Ol.	Mt.	Il.	Ap.	Cc.	Tn.	Total.
SiO_2	28.20	6.87	0.28	1.86	15.75	0.17					0.34	53.47
Al_2O_3	8.02	1.95	.18	1.58	.70							12.43
Fe_2O_3					2.74		3.45					6.19
FeO					1.52		1.55	0.66				3.73
MgO					2.79	.28						3.07
CaO					5.27				1.11	.50	.35	7.23
Na_2O		1.18		1.44	.78							3.40
K_2O	7.37		.11		.11							7.59
TiO_2								.74			.45	1.19
P_2O_5									.84			.84
SO_3				.62								.62
CO_2										.40		.40
Total	43.6	10.0	.5	5.5	29.6	.4	5.0	1.4	2.0	.9	1.1	100.16

Analyses of highwoodose and related rocks.

	I.	II.	III.	IV.	V.	VI.
SiO_2	53.47	53.98	52.05	51.75	51.94	0.891
Al_2O_3	12.43		15.02	14.52	15.78	.122
Fe_2O_3	6.19		2.65	5.08	4.07	.039
FeO	3.73		5.52	3.58	3.17	.051
MgO	3.07		5.39	4.55	3.48	.077
CaO	7.23		8.14	7.04	6.04	.116
Na_2O	3.40	3.94	3.17	2.93	3.44	.055
K_2O	7.59	7.39	6.10	7.61	7.69	.081
TiO_2	1.19		.47	.23	.39	.015
P_2O_5	.84		.21	.18	.59	.006
SO_3	.62	.38	.02		.29	.008
CO_2	.40	.64				.009
Total	100.16					

I. Microscopic analysis of highwoodose (nosean-syenite). L. V. Pirsson, analyst.

II. Partial chemical analysis of highwoodose (H_2O; 1.92; Cl. 0.03). W. F. Hillebrand, analyst.

III. Chemical analysis of borolanose (basic syenite) from Middle Peak, Highwood Mountains, Mont. E. B. Hurlburt, analyst.

IV. Chemical analysis of fergusose (fergusite) from head of Shonkin Creek, Mont. E. B. Hurlburt, analyst.

V. Trachiphyro-borolanose (syenite-porphyry) from dike at head of Shonkin Creek, Mont. W. M. Bradley, analyst.

VI. Molecular proportions of I.

In the analysis of the rock under description, as well as in the others, the general characteristic of the Highwood rocks—the concurrent high lime and potash—is clearly seen.

Classification in the new system.—From the analysis derived from the mode of the rock may be calculated its norm and place in the new classification.

Calculation of norm of highwoodose from near South Peak.

	Analysis.	Molecular ratio.	Or.	Ab.	No.	Qz.	Ac.	Di.	Mt.	Il.	Ap.	Wo.
SiO_2	53.47	0.891	486	150	32	23	24	160				16
Al_2O_3	12.43	.122	81	25	16							
Fe_2O_3	6.19	.039					6		33			
FeO	3.73	.051						3	33	15		
MgO	3.07	.077						77				
CaO	7.23	.116						80			20	16
Na_2O	3.40	.055		25	24		6					
K_2O	7.59	.081	81									
TiO_2	1.19	.015								15		
P_2O_5	.84	.006									6	
SO_3	.62	.008			8							
CO_2	.40	.009										
Total	100.16		81	25	8	23	6	80	33	15	6	16

Or	45.04	65.20
Ab	13.10	
No	5.68	
Qz	1.38	
Ac	2.77	33.97
Di	17.38	
Wo	1.86	
Mt	7.66	
Il	2.28	
Ap	2.02	
CO_2	.40	
Total	99.57	

Class, $\frac{\text{Sal}}{\text{Fem}}=\frac{65.20}{33.97}=1.9=$II, dosalane.

Order, $\frac{\text{L}}{\text{F}}=\frac{5.68}{58.14}=.09=$perfelic$=5$, germanare.

Rang, $\frac{K_2O'+Na_2O'}{CaO'}=\frac{130}{0}=\infty=$peralkalic$=1$, umptekase.

Subrang, $\frac{K_2O'}{Na_2O}=\frac{81}{49}=1.673=$dopotassic$=$highwoodose

The norm does not differ essentially from the mode, the main difference being in the splitting up of 27 per cent of alferric augite into 17 per cent of diopside and 10 per cent of femic and salic minerals. The rock has then in essence a normative mode. It is in the lower end of dosalane, not far from salfemane, and is clearly perfelic and in rang peralkalic. In subrang it is just within the border that separates highwoodose from ilmenose. Hence it differs somewhat from the type highwoodose from Highwood Gap, as may be seen by reference to the analysis of that rock, and approaches closer to salfemane, being much higher in lime, iron, and magnesia.

The texture is one common in granular rocks, consisting mainly of alkalic feldspars, a broad trachytoid one, produced by their lath shape, which, since it is megascopic, is designated "tracho" in the new classification. Thus the rock may be termed a "tracho-highwoodose." The rock is rather fine grained, and its appearance and character tends to show that it had crystallized rather quickly and in small mass and belongs to the "hypabyssal" types.

Classification in prevailing systems.—In the prevailing systems of classification this rock would be termed a "nosean-syenite," which is a distinct and rare member of the foyaite family. Osann[a] has shown that nosean occurs in the granular intrusive rocks of this family in the same manner as nephelite and sodalite, and has the same function. Hackmann[b] has shown its presence in nephelite-syenite of Umptek, in Kola Peninsula.

In the above occurrences this mineral accompanies nephelite, which is the dominant feldspathoid; but in the present instance no nephelite has been seen. It is possible that some of the analcite is secondary after nephelite, but it seems more probable that it is after nosean. The nosean-syenite in that case would be an equivalent to the sodalite-syenites of the Montana region described by Lindgren[c] and Merrill.[d]

GRANO-SHOSHONOSE (MONZONITE) OF HIGHWOOD PEAK.

Introductory.—This rock, whose field occurrence has been described in the discussion of the geology of Highwood Peak, has, as related, a somewhat different facies in different parts of its mass. The main type occurs next to the white pulaskose (pulaskite) forming the southwest part of the peak or intruded stock, and extends as the main portion of the mass until it merges into the fine, dense type of the north slopes and border.

In the outcrops the rock appears very dark, a deep stone color. At a distance it is almost black and in striking contrast with its neighbor, the white pulaskose. Under the hammer it is tough and breaks with difficulty, there being no tendency toward jointing on a small scale. It is fresh and yields excellent specimens.

Megascopic characters.—Examined on a freshly fractured surface, the rock is a dark stone gray with much the appearance of many rather fine-grained diorites or gabbros. It is composed of a mixture, in about equal parts, of blackish ferromagnesian and white feldspathic minerals. The average size of grain is from 1 to 2 mm. in diameter.

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[a] Neues Jahrb. für Min., 1892, vol. 1, p. 222.

[b] Kola, Fennia, II, No. 2, 1894, p. 121.

[c] Am. Jour. Sci., 3d ser., vol. 45, 1893, p. 286.

[d] Proc. U. S. Nat. Mus., vol. 18, 1895, p. 671.

None of the minerals exhibit any crystal form, but occasionally there can be seen the brilliant surface of a small particle of biotite.

Close examination shows also that former joints have been recemented by material of a feldspathic nature, injected after their formation. This phenomenon is discussed in a later paragraph.

Microscopic characters.—In thin sections the following minerals are found: Iron ore, apatite, biotite, diopside, labradorite, and soda orthoclase. The apatite is in the usual small, stout prismoids; the iron ore in small anhedra, generally associated with the biotite.

The pyroxene does not show any good crystal outlines, being in rough prismoids and grains. It has a pale-green color, and in places shows a faint but perceptible pleochroism, indicating probably a slight admixture of the ægirite molecule; in one instance a large anhedron has a perfectly colorless core. There is clearly not enough of the ægirite molecule in the mixture to classify the pyroxene as an ægirite-augite; it belongs in the diopside group, since a section of it cut nearly parallel to *b* (010) gives $c \wedge \mathfrak{c}=40°$. The thickness of the section, as shown by the feldspars, is about 0.03 mm., and the interference color is yellow of the second order, showing a maximum birefringence of 0.030. These are the properties of diopside. The mineral is spongy and incloses a large amount of iron ore and biotite. It is occasionally twinned on *a* (100). It is of a type common in the Highwood rocks.

The plagioclase is rather thickly scattered in the interspaces between the pyroxenes in rather small, short laths, ranging from 0.2 to 0.4 mm. in length. The laths are usually twinned according to both the albite and Carlsbad laws, and measurements according to Michel Lévy's method, in the zone perpendicular to *b* (010), show them to be labradorite of the composition $Ab_1 An_1$; thus in one section the symmetrical extinctions of the albite twins are 9°, of the Carlsbad half 25°; the section is therefore that of a labradorite $Ab_1 An_1$ cut about 42° from (100), or nearly parallel to the face *y* (201), and in covergent light the section shows the bisectrix α nearly centered in the field.

The mineral of final consolidation is the alkali feldspar, which is in broad, shapeless plates, inclosing the labradorite laths in a poikilitic manner. In this respect it recalls the rock of Monte Mulatto figured by Brögger,[a] but the plagioclase laths are smaller and more nearly like the type of Yogo Peak.[b] A section of the alkali feldspar was found parallel to *b* (010) and showing the obtuse bisectrix $\mathfrak{c}$. The cleavage parallel to *c* (001) was excellent, and a parting parallel to *a* (100) or *m* (110) permitted the orientation of the section, the angle between the two being 66°, while *a* (100) on *c* (001)=angle β is 63° 54′. The bisectrix α lies in the obtuse angle β; it is therefore positively

[a] Predazzo, 1895, p. 56.

[b] Pirsson, L. V., Petrography of Little Belt Mountains: Twentieth Ann. Rept. U. S. Geol. Survey, pt. 3, p. 476.

inclined and is 9° 30′ from the trace of *c* (001). These characters show that the mineral is a soda orthoclase or soda microcline (anorthoclase), the angle of extinction being that given by Fouqué for anorthose.[a] It may be added that the rock appears very fresh and without any alteration products.

Behavior with acids.—When the powdered rock is boiled with very dilute nitric acid, filtered, and the filtrate evaporated, a considerable amount of gelatinization ensues, indicating a mineral which yields to the acid.

Olivine has not been seen in the sections, although it may occur sporadically in the rock. The very small amount of chlorine, all of which is needed by the apatite, shows that not more than a mere trace of sodalite could be present. Nosean is also excluded by the test for SO_3, giving a negative result. Moreover, no isotropic material has been found in the sections, which confirms the above tests and also excludes analcite and leucite. Leucite, which is decomposed by acids, does not give gelatinous silica. From all this it is concluded that nephelite is probably present in a small amount in the rock, though it has not been found with certainty in the sections. It must be at any rate limited in amount, and, if present, plays an insignificant rôle. It will be noted that it occurs in the calculated norm.

Chemical composition.—The chemical composition of this rock is shown in the following table. Included in the table are analyses of several other rocks of similar characters, from localities in Montana, which have been described in previous publications. There is added an analysis of the monzonite from Monzoni given by Brögger and of a Swedish rock classed by him as a monzonite. It will be seen that the Highwood rock has similar features in its chemical composition, the rather low silica, rather high alumina, lime, iron and magnesia, moderate alkalies, and potash predominating over soda.

[a] L'étude des feldspath: Bull. Soc. Fran. Min., vol. 17, 1894, p. 148.

Analyses of shoshonose of Highwood Peak and related rocks.

No.	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.
SiO_2	51.00	54.42	52.81	54.20	50.35	52.05	52.80	56.25	0.850
Al_2O_3	17.21	14.28	15.66	15.73	15.76	15.02	19.99	20.50	.169
Fe_2O_3	2.41	3.32	3.06	3.67	2.32	2.65	3.63	1.85	.015
FeO	4.23	4.13	4.76	5.40	7.30	5.52	3.40	4.23	.058
MgO	6.19	6.12	4.99	3.40	7.40	5.39	3.20	2.54	.155
CaO	9.15	7.72	7.57	8.50	10.12	8.14	4.22	3.62	.164
Na_2O	2.88	3.44	3.60	3.07	2.75	3.17	3.10	5.91	.047
K_2O	4.93	4.22	4.84	4.42	3.89	6.10	7.74	4.80	.052
H_2O+	.63	.38	.93	.50	.45	.35	1.18	.83	------
H_2O-	------	.22	.16	------	------	------	------	------	------
TiO_2	.13	.80	.71	.40	.30	.47	1.00	.63	.001
P_2O_5	.33	.59	.75	.50	.39	.21	.70	------	.002
SO_3	.03	------	Trace.	------	------	.02	------	------	------
Cl	Trace.	------	.07	------	------	.24	------	------	------
Fl	------	------	Trace.	------	------	------	------	------	------
MnO	Trace.	.10	Trace.	.70	.35	Trace.	------	------	------
BaO	.34	.32	.24	------	------	.42	------	------	------
SrO	.14	.13	.09	------	------	.28	------	------	------
Total	99.60	100.19	100.24	100.50	101.38	100.03	100.96	101.16	------

I. Shoshonose (monzonite) from Highwood Peak, Montana. E. B. Hurlburt, analyst.

II. Monzonose (monzonite) from Yogo Peak, Little Belt Mountains, Montana. W. F. Hillebrand, analyst. Am. Jour. Sci., 3d ser., vol. 50, 1895, p. 473.

III. Monzonose (monzonite) from stock at head of Beaver Creek, Bearpaw Mountains, Montana. H. N. Stokes, analyst. Am. Jour. Sci., 4th ser., vol. 1, 1896, p. 357.

IV. Monzonose (monzonite) from Tyrol. V. Schmelck, analyst. Brögger, Triad. Erup. Predazzo, 1895, p. 24.

V. Kentallenose (monzonite, olivine) from Smalingen, Sweden. H. Santesson, analyst. Loc. cit., p. 46.

VI. Borolanose (basic syenite) from Middle Peak, Highwood Mountains, Montana. E. B. Hurlburt, analyst.

VII. Monzonite from Maros Peak, Borneo. Dr. Hinden, analyst. C. Schmidt in Sarasin's Celebes, vol. 4, 1901, p. 25.

VIII. Micromonzonite from Ambodimadiro, Madagascar, A. Lacroix, analyst. Roches alc. d'Ampasindava, Nov. Arch. du Muséum, 4th ser., vol. 1, 1902, p. 110.

IX. Molecular ratio of I.

Included in the table is a grano-borolanose of the neighboring Middle Peak stock. This is inserted to show how closely it resembles shoshonose in general chemical composition, the chief difference being a higher content of alkali. This difference is sufficient to produce important mineral variations, however, as shown in the description of this type.

Mineral composition or mode.—A consideration of the molecular ratios in the foregoing table and a study of the section give the following percentage composition by weight of the component minerals:

Percentage of minerals in shoshonose of Highwood Peak.

Iron ore	2
Biotite	10
Pyroxene	30
Labradorite	25
Soda orthoclase	33
Total	100

If it is assumed that the pyroxene has the same composition as in the shonkinite of Square Butte, given elsewhere; that the biotite has the same composition as the dark-green biotite of Monzoni analyzed by Rammelsberg;[a] that the labradorite is a rather acid type $Ab_4\ An_3$, and that the soda orthoclase has about half as much soda as potash, as is often the case, the rock will have the chemical composition given in the following table:

Calculated and determined composition of shoshonose.

	Calculated.	Found by analysis.
SiO_2	52.2	51.0
Al_2O_3	16.7	17.2
Fe_2O_3	2.4	2.4
FeO	2.6	4.2
MgO	6.4	6.2
CaO	9.5	9.1
Na_2O	3.2	2.9
K_2O	4.7	4.9

The agreement shows that the estimated amounts of the component minerals and their assumed composition must be nearly correct.

Texture.—The texture of this rock is a normal granitic one. It is xenomorphic rather than hypautomorphic, for none of the older ferromagnesian minerals show good crystal form; only the smaller lath-

[a] Min. Chem. Erg., 1886, p. 118.

shaped plagioclases have automorphic development. The texture, indeed, is that one typical of most stocks, of which the Highwood Peak mass furnishes a small but excellent example.

Classification in the new system.—The calculation of the norm from the analysis shows that the rock is a shoshonose.

Calculation of norm of shoshonose of Highwood Peak.

	Analysis.	Molecular ratios.	Or.	Ab.	An.	Ne.	Di.	Ol.	Mt.	Il.	Ap.
SiO_2	51.00	0.850	312	114	140	56	174	55			
Al_2O_3	17.21	.169	52	19	70	28					
Fe_2O_3	2.41	.015							15		
FeO	4.23	.058					19	23	15	1	
MgO	6.19	.155					68	87			
CaO	9.15	.164			70		87				7
Na_2O	2.88	.047		19		28					
K_2O	4.93	.052	52								
TiO_2	.13	.001								1	
P_2O_5	.33	.002									2
SO_3	.03										
Rest	1.11										
Total	99.60		52	19	70	28	87	55	15	1	2

Or	28.91	66.28
Ab	9.96	
An	19.46	
Ne	7.95	
Di	19.40	31.99
Ol	8.29	
Mt	3.48	
Il	.15	
Ap	.67	
Rest	1.14	
Total	99.41	

Class, $\frac{\text{Sal.}}{\text{Fem.}}=\frac{66.28}{31.99}=2.7=$ II, dosalane.

Order, $\frac{L}{F}=\frac{7.95}{58.33}=.136=$ perfelic $=5$, germanare.

Rang, $\frac{K_2O'+Na_2O'}{CaO'}=\frac{99}{70}=1.4=$ alkalicalcic $=3$, andase.

Subrang, $\frac{K_2O'}{Na_2O'}=\frac{52}{47}=1.1=$ sodipotassic $=3$, shoshonose.

Grad, $\frac{P+O}{M}=\frac{19.40}{3.63}=5.3=$ dopolic $=2$, shoshonate.

Subgrad, $\frac{(MgFeO)+CaO''}{(K_2Na_2)O''}=\frac{300}{0}=$ permirlic, 1, shoshonote.

Thus, in the new system, if the texture is considered and the classification be carried down into the grad and subgrad the rock is granoshoshonote. All that this name means, then, is indicated in the table above. Since the mode is not a normative one, and as, instead of olivine and feldspathoid molecules in the norm, biotite is actually developed in the mode, the rock may be termed a biotitic granoshoshonote. This name is a concise expression for a granular rock consisting of ferromagnesian and feldspathic minerals which has the following characteristics:

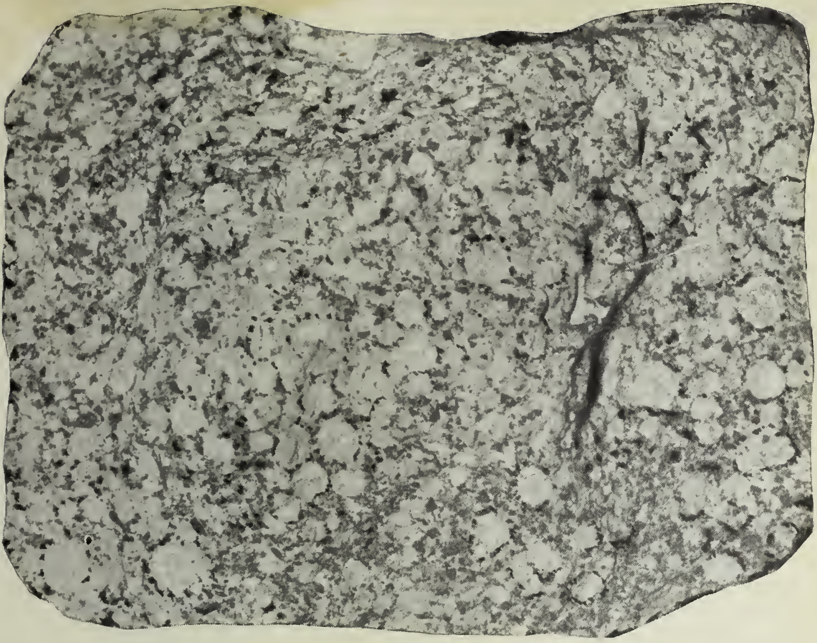
The ferromagnesian minerals are present in notable quantity, but are exceeded in amount by the feldspathic minerals; the feldspars are not accompanied by any notable amount of feldspathoids; considerable anorthite is present molecularly, but is exceeded in amount by the alkali-feldspar molecules, in which the potash and soda are about equal; of the ferromagnesian minerals, the iron ores are greatly dominated by the other ferromagnesian minerals which contain few or no alkaline molecules; olivine and a feldspathoid, which might have been expected to occur in the rock, are replaced by biotite, whose amount, however, is not large, not exceeding 12.5 per cent. This name, then, surely gives a rather exact idea of the character of the rock, but it does not tell anything of its manner of occurrence, of the shape of its mass, of its relations to related rocks, and of its geologic age, for, according to the writer's belief, these things have no place in a systematic classification, although they may be of the greatest importance and of the utmost interest in other ways.

Classification in prevailing systems.—In the prevailing systems the rock is a typical monzonite both mineralogically and chemically. Since the monzonites form a group of rocks of what may be termed mean composition, they vary in different directions according to the rock complex in which they occur and with which they show affinities. In the present case the monzonite is related to the special group of alkaline rocks occurring in the Highwoods, and its genetic relationship to this particular group is shown by the presence of augite similar to that in the other members and by the occurrence of small and otherwise unimportant quantities of feldspathoid minerals. There are also other points of resemblance, but it is often as difficult to describe the minute and subtle features which indicate that a rock belongs to a certain geographic class or petrographic province as it is to portray the characteristics which distinguish one man from another.

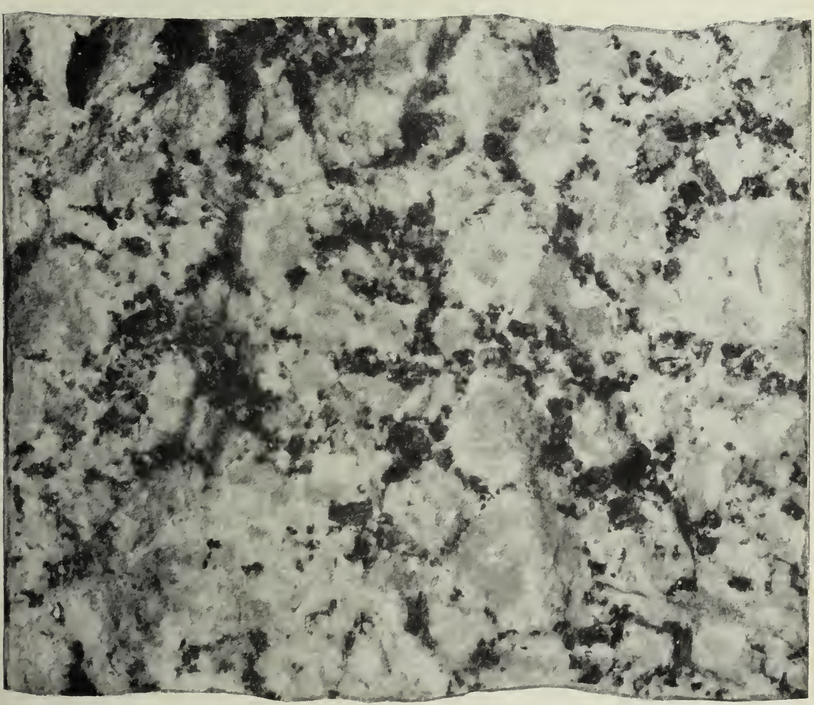
The alliance between the monzonites and certain alkaline rocks has been already pointed out by Rosenbusch,[a] and the present case adds another example to the list.

Dikelets in shoshonose (monzonite).—As previously mentioned, the surface of the rock is everywhere seamed by very fine lines of light-colored feldspathic material. This is due to veins or dikelets which have been injected into it. It appears to the writer that the only way in which these dikelets, which are very common in many granular igneous rocks, can be explained is by the hypothesis that they are later injections along joint planes formed by the contraction of the cooling rock mass. This seems confirmed also by the toughness of the rock body and its present lack of small joint planes. These previously existed, having been formed by the contraction of the cooling rock, but have been everywhere healed by a later intrusion of feldspathic material. This, on the rock surfaces, produces lines,

[a] Mikr. Phys. Mass. Gesteine, 3d ed., 1895, p. 124; Elemente der Gesteinslehre, 1898, p. 108.



A.



B.

FERGUSITE FROM HIGHWOOD MOUNTAINS.

at first glance scarcely noticeable, since the films, which have been broken across, are often as thin as paper. This healing of the initial jointing by later processes may be ascribed to pneumatolytic action, and it would seem as if the material must have been carried in by heated liquids or gases, as the width of most of the cracks is so slight that it is impossible to imagine a viscous molten fluid forcing its way along them for any distance.

Contact facies of shoshonose (*monzonite*).—As mentioned elsewhere, the main type just described passes on the north side of the mass into outcrops and rock piles of a dense, very dark, and somewhat flinty-looking variety with a platy cleavage. On exposed surfaces it weathers to a dark gray, mottled by larger mineral grains. From its relations in the field this rock is believed to be a contact form of the type described above. In thin sections it shows the same minerals, but it has a somewhat different texture. The augite is in smaller grains, but has rather better crystal form, while the feldspathic components are in very minute microlites and grains, the contrast causing the larger augites to appear like phenocrysts in a feldspar groundmass. The iron-ore grains are commonly surrounded by a thin biotite mantle. These minerals are not large enough to give the rock a porphyritic habit, and it might be called a grano-shoshonose (micromonzonite).

FERGUSOSE (FERGUSITE) OF ARNOUX STOCK.

Occurrence.—The main stock at the head of Shonkin Creek lies at the intersection of the parallel of 47° 15′ north latitude and the meridian of 110° 30′ west longitude. About 2 miles northwest of it is a much smaller stock intruded into the basaltic flows and breccias. This stock is in general circular in plan and is a little over a mile in diameter. It lies on the north slopes of the main ridge and is dissected by a ravine whose waters are tributary to Shonkin Creek. The locality was not seen by the writer, but the description of the main type composing this small stock is based on material collected by Mr. Weed.

Megascopic characters.—The general character of this type is that of a light-gray massive rock of rather coarse grain. This general color effect is given by the mingling of a pale flesh-colored component with a much smaller amount of a dark-colored one. On closer inspection it is seen that the light component is in round grains running from 5 to 2 mm. in diameter, and averaging about 3 mm. These grains are clearly of a feldspathoid mineral, and in outline they are sometimes sharply, sometimes more or less poorly, defined. In some places they are distinctly separated; in others they are closely crowded. Their general appearance is shown on Pl. VI, *A*, which presents them of natural size. In Pl. VI, *B*, they are seen on a small portion of the rock surface magnified three times. It can be plainly seen in Pl. VI, *B*, that all of the light component consists of these rounded masses or of small anastamosing offsets from them. This is an important point in the classification of the rock and will be alluded to later on. As will be shown, they are pseudoleucites. The dark component which fills the interspaces between these round grains of pseudoleucite is a blackish-green augite in small irregular masses showing an occasional dull-lustered cleavage face. The largest of them are rather columnar and about 2 mm. long. Here and there at times a small bronzy-lustered plate of biotite is seen. These, intermingled and outlined in places by little stringers of feldspathoid substance, form a sort of granular interfilling between the larger pseudoleucites. This appearance is shown on Pl. VI, *B*.

Microscopic characters.—In thin sections the minerals observed are apatite, iron ore, olivine, biotite, augite, orthoclase, nephelite, and zeolites with kaolin.

The apatite is in small, stout prisms of the character usual in basic rocks. The iron ore is in small formless grains. The amount of these minerals is small. Of the olivine, only a few scattered, mostly formless grains were seen in the sections. It is fresh and of the usual character. Its amount is entirely too small for it to be reckoned as one of the normal constituents of the type; its occurrence must be regarded as sporadic. Biotite is seen in scattered shreds without crystal form. It has the usual brown pheochroic character, and only a small quantity is found.

The augite is the only ferromagnesian mineral which is important. It is of a green color and very similar to the augites which have been described as characteristic of shonkinose (shonkinites). It is slightly pleochroic in tones of green, between a slightly grayish cast and a yellowish olive. Its angle of extinction is large, about 45°, and it is clear that the diopside molecule predominates and that it is not an ægirite-augite, though probably a little of the ægirite molecule is present. In its cleavage and other characters it offers nothing of especial interest.

In plain light the areas of white feldspathoid mineral are colorless save for a brown tone here and there, caused by a partial kaolinization, which renders the material turbid. In polarized light they are neither isotropic nor do they show the characteristic twinning of large leucites. They are composed of irregular patches and rudely fibrous radiating bundles of minerals having the birefringence and properties of alkali feldspars and nephelite. They are, indeed, similar to occurrences already described from Brazil,[a] Arkansas,[b] and Montana.[c]

[a] Graeff, Neues Jahrb. für Min., 1887, vol. 2, p. 257.
[b] Williams, J. F., Ann. Rept. Arkansas Geol. Surv. for 1890, vol. 2, p. 268.
[c] Pirsson, L. V., Am. Jour. Sci., 3d ser., vol. 50, 1895, p. 395; 4th ser., vol. 2, 1896, p. 194.

The masses have a peculiar mottled, marbled effect, due to the intergrowth of the two minerals, and in a few very small spots are penetrated by clear areas of a colorless isotropic mineral which is held to be secondary analcite. In some places very small secondary feldspars with clean-cut crystal outlines seem to have formed. As the optical tests on these intermingled feldspathic minerals gave somewhat indefinite results, it was determined to confirm them by chemical tests. For this purpose a piece of the rock was broken into fine fragments and out of these was carefully picked about half a gram of material which contained only the white feldspathoid substance and in which was no dark mineral. Thus the possibility of any contaminating olivine was avoided. The fragments were reduced to powder, which was then boiled for a moment with very dilute nitric acid, the solution was filtered, and the filtrate evaporated. As the filtrate diminished in volume an abundant gelatinization ensued. The solution gave an abundant and powerful flame test for soda, showing clearly the presence of nephelite in some quantity. The solution gave no reaction for chlorine or sulphuric anhydride, which indicated that there was no sodalite or nosean present. The undissolved residue consisted of the alkali feldspars.

Chemical composition.—The complete analysis of this rock is given in the next table. The noteworthy features of it are the rather low silica and alumina, the medium iron and magnesia, and the high lime and alkalies, with the strong predominance of the potash. Analyses of some other leucitic rocks are given for comparison. The silica, it is to be noted, is rather high for a leucite rock, owing to the fact that the greater part of the original leucite has been turned into orthoclase. It is not higher, on the other hand, than the rock from Brazil or the wyomingite, but these have higher alkalies and thus a higher amount of leucite.

In III and IV, typical leucitites, as that term is now used, the general relations of the oxides is very close to those in fergusose, the higher silica being the most marked difference. It thus represents very well in a chemical way the extrusive leucitic magmas.

In regard to analysis II, it would appear as if the separation between alumina and magnesia were doubtful, since Rosenbusch[a] remarks that it contains more pyroxene than III, while the analysis would indicate an extremely small amount of pyroxene. The amount of alumina is so large as to be almost marvelous in a rock with the mineral composition as described.

The comparison with the analysis of missourite is interesting. It is at once observed that missourite is a much more basic rock; it is lower in silica, alumina, and alkalies, and much higher in lime and magnesia, the iron remaining the same. Missourite is thus much richer in augite and has abundant olivine. Fergusose (fergusite) is a

[a] Elemente der Gesteinslehre, 1898, p. 350.

Analyses of fergusose from near Shonkin Creek and leucitic rocks.

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.
SiO_2	51.75	52.16	46.51	45.99	46.06	53.70	46.48	0.863
Al_2O_3	14.52	20.14	11.86	17.12	10.01	11.16	19.00	.142
Fe_2O_3	5.08	6.45	7.59	4.17	3.17	3.10	4.74	.032
FeO	3.58		4.39	5.38	5.61	1.21	2.30	.050
MgO	4.55	1.54	4.73	5.30	14.74	6.44	2.49	.114
CaO	7.04	4.64	7.41	10.47	10.55	3.46	4.35	.125
Na_2O	2.93	5.73	2.39	2.18	1.31	1.67	8.46	.047
K_2O	7.61	8.12	8.71	8.97	5.14	11.16	6.78	.081
$H_2O+110°$	2.25	1.39	2.45	.45	1.44	2.61	3.31	.125
$H_2O-110°$			1.10			.80		
CO_2							.36	
TiO_2	.23	Trace.	.83	.37	.73	1.92	1.22	
P_2O_5	.18	(?)	.80		.21	1.75	.15	
SO_3	Trace.	(?)	Trace.		.05	.06	.19	
Cl	.05	Trace.	.04		.03	.03	.08	
MnO	Trace.	Trace.	.22		Trace.	.04	Trace.	
BaO	.30	(?)	.50	.25	.32	.62	(?)	
SrO	.07	(?)	.16	None.	.20	.19	(?)	
Li_2O	Trace.						(?)	
Total	100.14	100.17	99.73	100.65	99.57	[a]100.21	99.91	

[a] Including traces of rare elements and deducting O=Fl=0.44 per cent.

I. Fergusose (fergusite) from Arnoux core, head of Shonkin Creek, Highwood Mountains. E. B. Hurlburt, analyst.

II. Janeirose (leucitophyre) from Sierra de Caldas, S. Paulo, Brazil. F. W. Dafert, analyst. Hussak, Neues Jahrb. für Min., 1892, vol. 2, p. 149.

III. Chotose (leucitite) from Bearpaw Peak, Bearpaw Mountains, Montana. H. N. Stokes, analyst. Weed and Pirsson, Am. Jour. Sci., 4th ser., vol. 2, 1896, p. 147.

IV. Albanose (leucitite) from Capo di Bove near Rome, Italy. H. S. Washington, analyst. Am. Jour. Sci., 4th ser., vol. 9, 1900, p. 53.

V. Missourote (missourite) from Shonkin core, head Shonkin Creek, Highwood Mountains. Weed and Pirsson, Am. Jour. Sci., 4th ser., vol. 2, 1896, p. 321.

VI. Orendose (wyomingite) from Leucite Hills, Wyoming. W. F. Hillebrand, analyst. W. Cross, Am. Jour. Sci., 4th ser., vol. 4, 1897, p. 130.

VII. Arkansose (leucitite) from Etinde Volcano, Cameroon Mountains, Africa. M. Dittrich, analyst. E. Esch. Sitzb., k. Preuss, Akad. Wiss., Berlin, Math. Phys. Kl., 1901, p. 299.

VIII. Molecular proportions of I.

leucocratic (salic) type in Brögger's sense, though not strikingly so, while contrasted with it missourite is melanocratic (femic); thus fergusose represents the leucitites, missourite the leucite-basalts.

In regard to the surface lavas Rosenbusch[a] says: "The two divisions of the leucite rocks, the leucitites, free from olivine, and the olivine-bearing leucite-basalts, are distinguished not alone by the presence or absence of the olivine. The typical leucitites, in contrast to the typical leucite-basalts, are characterized much more by a far smaller content in iron ores and augite." Thus in the Highwood Mountains the intrusive representatives of leucite rocks, fergusite and missourite, have the same difference.

Texture.—The texture of the rock is best seen from the photographs shown on Pl. VI. A glance at the picture of the hand specimen gives the impression that the rock is a porphyry. When the rock is examined, however, it is seen that this idea is not correct. By porphyritic texture one understands that certain minerals possess a definite well-cut crystal form and that they are embedded in a distinct groundmass. This is not the case here, for all of the leucite is in approximately rounded grains with well-defined though crystallographically not well-bounded grains of augite between them. There can not be distinguished two periods of formation of any mineral, nor two types of any mineral formed simultaneously. The structure is much more to be compared to that of certain syenites which are characterized by a tabular development of the feldspar. That is, the feldspathic minerals are dominant, and have attempted to take their own form and have approximately done so, compelling the ferromagnesian elements to crystallize in between them.

It is also to be noted that, whereas in a mineral which crystallizes in some form other than the leucitohedron and to which it tends to approximate the cross sections taken at random would have a variety of shapes, producing an effect of irregularity or of granular texture, in the case of leucite the endeavor to assume the form of the tetragonal trisoctahedron or leucitohedron results in the production of spheres or spheroids, and every cross section is either a circle or approximately one, thus tending to destroy the effect of irregularity and to produce a pseudoporphyritic structure. Aside from this, the rock has in the hand specimen the solidity, firmness of texture, and general appearance of the granitic types of rocks, as suggested by Pl. VI, *B*.

Classification in the new system.—In the new system this rock occupies a definite position in the subrangs under laurdalase, and as it is the only described analysis under this subrang its name has been given to the division.[b] This may be seen in the following calculation of its norm.

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[a] Mikr. Phys. Mass. Gesteine, 3d. ed., 1895–96, p. 1232.

[b] Cross, Iddings, Pirsson, and Washington, Quantitative Classificationof Igneous Rocks, p. 268.

Calculation of the norm of fergusose.

	Analysis.	Molecular ratio.	Or.	Ab.	An.	Ne.	Di.	Ol.	Mt.	Il.	Ap.
SiO_2	51.75	0.863	486	42	28	80	216	10			
Al_2O_3	14.52	.142	81	7	14	40					
Fe_2O_3	5.08	.032							32		
FeO	3.58	.050					13	2	32	3	
MgO	4.55	.114					95	19			
CaO	7.04	.125			14		108				3
Na_2O	2.93	.047		7		40					
K_2O	7.61	.081	81								
TiO_2	.23	.003								3	
P_2O_5	.18	.001									1
Cl	.05	.001									1
Rest	2.62										
Total	100.14		81	7	14	40	108	10	32	3	1

Or	45.04	63.96
Ab	3.67	
An	3.89	
Ne	11.36	
Di	23.75	33.50
Ol	1.53	
Mt	7.42	
Il	.46	
Ap	.34	
Rest	2.62	
Total	100.08	

Class, $\frac{\text{Sal.}}{\text{Fem.}}=\frac{63.96}{33.50}=1.9=$II, dosalane.

Order, $\frac{\text{L}}{\text{F}}=\frac{11.36}{52.60}=.21=$lendofelic$=6$, norgare.

Rang, $\frac{K_2O'+Na_2O'}{CaO'}=\frac{128}{14}=9.1=$peralkalic$=1$, laurdalase.

Subrang, $\frac{K_2O'}{Na_2O'}=\frac{81}{47}=1.7=$dopotassic$=2$, fergusose.[a]

Mineral composition or mode.—The rock was too coarse grained for satisfactory measurement under the microscope, and it was therefore measured megascopically, with the following results:

	Units measured.	Volume, per cent.		Specific gravity.				Weight, per cent.
Sal	334	70.3	×	2.6	=	1,827.8	=	65.1
Fem	141	29.7	×	3.3	=	980.1	=	34.9
Total	475	100.0				2,807.9		100.0

These results agree so closely with those calculated for the norm given above that we may say that the rock has a normative mode.

Classification in prevailing systems.—In the prevailing systems of classification this rock has also a distinct place of its own and should be called fergusite. This is due to its mode of occurrence, mineral

[a] When this name was chosen it was supposed the Arnoux stock was in Fergus County. Recent maps show the locality a little north of the line, in Choteau County. Boundary lines in these thinly settled regions are not very accurately known, so the error, if it should be confirmed, is not a matter of importance.

and chemical composition, and texture. It is defined as a granular intrusive rock consisting of dominant leucite with subordinate augite. Small amounts of accessory minerals may be present, such as apatite, iron ores, biotite, sporadic olivine, etc., but the true determinants are the leucite and the augite. The rock is therefore the granular representative of the leucitites, and it bears the same relation toward them that missourite bears to the leucite-basalts, and thus fills a gap in this system of classification.

It is true that in the present example the leucite has been changed to pseudoleucite, but that does not alter the validity of the type. In a large part, probably the major part, of the missourite of the Shonkin stock the leucite is also changed to pseudoleucite, but, as mentioned under the description of missourite, in places the leucite is still left unchanged and in other places it occurs changed and unchanged in the same specimen. A detailed study of all parts of the Arnoux stock would probably show the same phenomena, or if the mass could be studied at various vertical levels it might show the same variations. In hand specimens of missourite and other altered leucite rocks of the Highwoods it is impossible to distinguish the unchanged from the altered leucite. Only when studied under the microscope does the real character appear. Therefore the type may be considered as a well-established one, although the specimen described is not a perfect unaltered example.

GRANO-BOROLANOSE (BASIC SYENITE, SHONKINITIC TYPE) OF MIDDLE PEAK.

The rock forming the Middle Peak stock closely resembles the shoshonose (monzonite) of Highwood Peak in appearance and in chemical composition. It differs from it, however, in important particulars, as will be seen in the following description. It has a border facies which varies in several respects from the main type.

Megascopic characters.—On a freshly fractured surface the rock has a medium-gray color and a moderately even grain, the individual components being in the neighborhood of 1 mm. in diameter. On inspection it is seen to be made up of light and dark minerals in about equal proportions. The light feldspathic minerals are devoid of distinct form, but the ferromagnesian component is chiefly a dark-green augite in short, stout, columnar forms without good terminations. The mingling of these two gives the rock at a short distance the general appearance presented by many medium-grained diorites.

Microscopic characters.—Under the microscope the following minerals are seen: Iron ore, apatite, biotite, olivine, augite, and alkali feldspar.

The iron ore is at present in rather abundant small grains; a few larger ones were seen. It is generally surrounded with narrow mantles of a red-brown pleochroic biotite. There are also a few isolated shreds of this biotite, but its total amount is small and its rôle insignificant. There is a moderate amount of a rather fresh olivine present in rounded crystals which average about 0.4 mm. in diameter. In many places where it touches alkali feldspar there is a very narrow zone of a green pleochroic biotite separating them.

Two varieties of augite are present, and it is by far the most abundant ferromagnesian mineral. The first variety, which is rare, is a colorless or faintly green diopside in long, slender, well-formed prisms. It has a wide extinction angle, strong birefringence, and is often twinned on (100). The other pyroxene, the most abundant dark mineral, is an augite of a green color with a tinge of brown. It is present in short, stout prismoids and grains, and also at times in larger columns, which are well crystallized. These attain a length of 4 mm. It has a good cleavage, is nonpleochroic, and often zonally built. It has inclusions of iron ore, biotite, and brownish glass, and the largest crystals are sometimes spongy and filled with these earlier products of crystallization.

The light-colored feldspathic component appears to consist wholly of alkali feldspars. These laths are in rather thin tabular crystals which are almost always carlsbad twins. No albite or other twinning was observed. The laths do not contain any microperthite intergrowths, but are zonally built. In sections parallel to the clinopinacoid, which are easily recognized by their nearly square outlines, lack of twinning, and medium birefringence, the cleavage parallel to the base (001) is seen as a series of fine lines with moderately high power. The direction of the vertical axis is told by a rather poor prismatic parting and the arrangement of minute inclusions parallel to the prism faces. The angle between these two directions was measured at 65°, which is approximately equal to the angle β of feldspar. On such faces the bisectrix $\mathfrak{c}$ emerges and the plane of the optic axis gives an extinction angle of 5° with the base of the basal cleavage in the obtuse angle β. These properties are found in the interior of the crystals, and they show that this portion of them is composed of a rather pure orthoclase. Toward the outer boundary the birefringence gradually rises a little and the extinction angle also increases to 12° and over. This shows that the inner kernel of orthoclase gradually changes to a soda orthoclase by assumption of the albite molecule, giving rise to the zonal structure mentioned.

Between these feldspars lie the final products of crystallization—a fine mosaic of interlocking granules of alkali feldspar. These small areas have an appearance which is much like that of the groundmass of some feldspathic dike rocks or of trachytoid lavas having a microgranitic structure. They were carefully searched for quartz or nephelite, and while no quartz is present, it can not be said that nephelite is not. Under the circumstances and considering the chemical composition of the rock, it would be natural to expect nephelite, but the grains were too fine for any definite determination, and the presence of olivine precludes the usual gelatinization test. The writer has found that gelatinization and staining with eosin is an unsatisfactory and unsafe test where minute amounts of nephelite are concerned, and it was not tried. If a safe means of determining very small amounts of nephelite mixed in with alkali feldspars could be discovered it would be of great service to petrographers.

Some of the small areas mentioned above are rounded and in plain light appear pale brown from incipient kaolinization. It is barely possible that they may be pseudoleucites, a suspicion aroused by the chemical composition of the rock.

Chemical composition.—The chemical composition of this rock is shown in I of the table of analyses on page 92.

The characteristic chemical feature is the combination of high oxides of the alkaline earths and high alkalies, and more especially of lime and potash. These give the rock a marked chemical individuality—the Highwood stamp. The alumina is moderate, the silica rather low. These characters are shared by two other rocks of the district (II, III), which will be described in a later paragraph. There is a general resembance of these types in the distinguishing features to borolanite (IV), which is also low in silica, contains a good deal of lime, and is high in potash; its alumina is no doubt too high, in part it contains P_2O_5 and probably some MgO. Another rock which is similar in the same way is that variety of the nephelite-syenite complex of Magnet Cove described by Washington, first as shonkinite and later as covite, whose analysis is given under V. In the new system of classification it falls in the same subrang. The chemical difference between these types and the shonkinoid ones is shown by comparison with the analysis of the montanose (shonkonite) of the Shonkin Sag laccolith given under VI. The lower alumina and alkalies and the larger amount of bivalent oxides produce a marked difference in the mineral composition, which is easily seen in a comparison of the hand specimens. The same is also true of the shoshonose (monzonite) of Highwood Peak; in the hand specimens, as previously mentioned, this rock very closely resembles that of Middle Peak, but the microscope shows a considerable amount of plagioclase, which is produced by the higher lime and lower alkalies, and which is wanting in the Middle Peak rock.

Analyses of borolanose and related rocks.

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.
SiO_2	52.05	50.11	50.00	47.8	49.70	47.88	51.00	0.867	0.835	0.833
Al_2O_3	15.02	17.13	19.36	20.1	18.45	12.10	17.21	.147	.168	.182
Fe_2O_3	2.65	3.73	3.87	6.7	3.39	3.53	2.41	.017	.023	.024
FeO	5.52	3.28	2.67	.8	4.32	4.80	4.23	.076	.046	.037
MgO	5.39	2.47	2.18	1.1	2.32	8.64	6.19	.135	.062	.055
CaO	8.14	5.09	4.96	5.4	7.91	9.35	9.15	.145	.091	.089
Na_2O	3.17	3.72	3.63	5.5	5.33	2.94	2.88	.052	.060	.059
K_2O	6.10	7.47	8.52	7.1	4.95	5.61	4.93	.065	.080	.091
H_2O+	.35	4.47	3.53	2.4	1.09	1.52	.63	------	------	------
H_2O-	------	------	.46	------	.25	.70	------	------	------	------
CO_2	None.	------	------	------	------	.12	------	------	------	------
TiO_2	.47	.82	------	.7	1.33	.77	.13	.006	.010	.006
P_2O_5	.21	.67	------	(?)	.40	1.11	.33	.001	.005	.002
SO_3	.02	.08	------	.4	------	None.	.03	------	.001	------
Cl	.24	.07	------	------	------	Trace	Trace	.006	.002	------
Cr_2O_3	None.	------	------	------	------	.04	------	------	------	------
NiO	------	------	------	------	------	Trace	------	------	------	------
MnO	Trace.	Trace.	------	.5	Trace	.15	Trace	------	------	------
BaO	.42	.63	------	.8	------	.46	.34	------	------	------
SrO	.28	.35	------	------	------	.13	.14	------	------	------
	100.03	100.09	------	------	------	------	------	------	------	------
Cl=O	.06	.02	------	------	------	------	------	------	------	------
Total	99.97	100.07	99.18	99.3	99.44	99.99	99.60	------	------	------

I. Borolanose (basic syenite) from Middle Peak. E. B. Hurlburt, analyst.
II. Borolanose (basic syenite) from Palisade Butte. H. W. Foote, analyst.
III. Borolanose (basic syenite) from Shonkin Sag laccolith. W. F. Hillebrand, analyst. (Partial analysis; TiO_2, P_2O_5, etc., not determined; in part with Al_2O_3, which is high.)
IV. Borolanose (borolanite) from Lake Borolan, Sutherland, Scotland. J. Hort Player, analyst. Horne and Teall, Trans. Roy. Soc. Edinburgh, vol. 37, pt. 1, 1892, p. 163.
V. Borolanose (covite) from Magnet Cove, Arkansas. H. S. Washington, analyst. Jour. Geol., vol. 9, 1901, p. 612.
VI. Montanose (shonkinite) from Shonkin Sag laccolith. W. F. Hillebrand, analyst. (Includes ZrO_2, 0.03 and V_2O_3, 0.04.)
VII. Shoshonose (monzonite) from Highwood Peak. E. B. Hurlburt, analyst.
VIII. Molecular proportions of I.
IX. Molecular proportions of II.
X. Molecular proportions of III.

Mineral composition or mode.—In determining the actual mineral composition of the rock, it was found necessary in using Rosiwal's method to measure together the alkali feldspars and any nephelite that might be present, since, for the reasons given in the microscopic description, it was impossible to discriminate between them. In all 4,390 units were measured in 114 measurements, giving an average of 38 units to each measured area. The following quantitative composition is derived:

Mineral composition or mode of borolanose of Middle Peak.

	Units measured.	Volume, per cent.		Specific gravity.				Weight, per cent.
Feldspar	2,465	60.25	×	2.6	=	156.6	=	53.2
Augite	1,275	28.81	×	3.3	=	95.0	=	32.3
Biotite	175	3.98	×	3.0	=	11.9	=	4.0
Olivine	60	1.37	×	3.3	=	4.5	=	1.7
Iron ore	200	4.55	×	5.2	=	23.6	=	7.9
Apatite	35	.89	×	3.2	=	28.4	=	.9
Total	4,390	99.85				294.2		100.0

Classification in the new system.—The position of the rock in the new system is given in the following calculation, which shows it to be borolanose near shonkinose. On account of its granular texture it should be called grano-borolanose.

Calculation of the norm of borolanose.

	Analysis.	Molecular ratio.	Or.	Ab.	An.	Ne.	So.	Di.	Ol.	Mt.	Il.	Ap.
SiO_2	52.05	0.867	390	84	66	52	18	218	40			
Al_2O_3	15.02	.147	65	14	33	26	9					
Fe_2O_3	2.65	.017								17		
FeO	5.52	.076						31	22	17	6	
MgO	5.39	.135						78	57			
CaO	8.14	.145			33			109				3
Na_2O	3.17	.052		14		26	12					
K_2O	6.10	.065	65									
TiO_2	.47	.006									6	
P_2O_5	.21	.001										1
Cl_2	.24	.003					3					
Rest	1.07											
Total	99.97		65,	14	33	26	3	109	40	17	6	1

Or	36.14	62.94
Ab	7.34	
An	9.17	
Ne	7.38	
So	2.91	
Di	24.53	35.95
Ol	6.23	
Mt	3.94	
Il	.91	
Ap	.34	
Rest	1.07	
Total	99.96	

Class, $\frac{\text{Sal.}}{\text{Fem.}}=\frac{62.94}{35.95}=1.8=$II, dosalane (near salfemane).

Order, $\frac{L}{F}=\frac{10.29}{52.65}=.19=$lendofelic$=6$, norgare (portugare).

Rang, $\frac{K_2O'+Na_2O'}{CaO'}=\frac{117}{33}=3.6=$domalkalic$=$essexase (monchiquase).

Subrang, $\frac{K_2O'}{Na_2O'}=\frac{65}{52}=1.2=$sodipotassic$=$borolanose (shonkinose).

It is of interest to compare the norm as calculated above with the mode obtained by measurement. For this purpose the feldspathic components of both are united under the symbol F, and ilmenite with magnetite.

Comparison of norm with mode of borolanose.

	I.	II.	III.
F	62.9	53.2	53.7
Di	24.5	32.3	33.7
Bi		4.0	
Ol	6.2	1.7	6.2
Mt	3.8	7.9	3.8
Ap	.3	.9	.3

Under I is given the norm and under II the mode. The chief difference lies in the relation of feldspar to pyroxene, and is caused by the fact that in the norm is included 9.2 per cent of anorthite. The lime silicate is, however, actually not in the feldspars but in the augite, as shown by the study of the section. If it were transferred to the augite the mode would assume the proportions seen in III and the close agreement of the ratios of feldspar to augite is seen at once. The lime may not be present in the augite exactly as anorthite, but as a closely related lime silicate.

It is interesting to observe that this relation in the feldspars makes the chief difference between this rock and the shoshonose (monzonite) of Highwood Peak. There the anorthite has united with the albite to make plagioclase; here the lime as a silicate has gone into pyroxene.

Classification in prevailing systems.—In the prevailing systems this rock does not have any very definite position. If the relative quantities of the components and its associations and chemical composition are disregarded and the fact that it consists in the main of alkali feldspars and augite is considered, it would be called an augite-syenite. There are certainly not enough feldspathoids present to place it in the nephelite-syenite family. If the basic character shown by the analysis, the relative quantities of the minerals, and its regional rock associations are taken into account, it appears as a type transitional between syenite and shonkinite, and might then be called a shonkinitic syenite.

Border facies.—At the contact the rock just described has a rather distinctly marked endomorphic contact facies. It appears to be somewhat coarser in grain and has a slight tendency to a porphyritic texture. This is due in the main to the fact that the orthoclase feldspars appear in large, thin plates of considerably greater size than in the prevailing type and tend to be roughly oriented parallel to the contact in a rude flow structure which gives the rock a slight tendency to split in this direction.

Under the microscope the minerals of the general type just described are found with some little variation. In the contact rock the iron ore and apatite, and perhaps biotite, of a rich pleochroic brown, are somewhat more abundant than in the type rock. The augite varies considerably in size and is a clearer green color, passing to a rich sea green on the border. It is, however, nonpleochroic in spite of this addition of the ægirite molecule, and hence it must still be chiefly diopside. The feldspars are in carlsbad twins, and in small angular interspaces are occasional clear isotropic areas of unaltered sodalite, whose occurrence serves to make almost certain the presence or former presence of a lenad (feldspathoid) mineral in the main type.

The main feature of this border facies is the occurrence of hornblende associated with diopside. The hornblende appears to some extent to replace the diopside, since in those places where it is abundant diopside is rare, and vice versa. It is a compact homogeneous variety, is not seen intergrown with diopside, and appears in all respects like a primary mineral. It is much like arfvedsonite in a general way, and is at all events, considering its habitat and associates, one of the alkalic group of hornblendes. It is strongly pleochroic as follows:

$\mathfrak{a}$=Ocher-yellow.
$\mathfrak{b}$=Dark olive.
$\mathfrak{c}$=Dark olive-green.

The absorption is very strong and the arrangement rather peculiar: $\mathfrak{b}>\mathfrak{c}>\mathfrak{a}$. On account of the strong absorption, which is almost equal to a colored tourmaline, it was difficult to measure the angle of extinction on the clinopinacoid of $c \wedge \mathfrak{c}$, but it is certainly as much as 30° and probably more—a most unusual angle for a hornblende. The double refraction is rather weak. It occurs in well-shaped prisms with poor terminations. The prisms are stout rather than slender, and the prismatic cleavage is well marked.

This hornblende is unique in its characters and the writer knows of none exactly like it. It does not occur in any other rock in the Highwoods, its nearest affinity being the green variety in the sodalite-syenite (pulaskose) of Square Butte, from which it differs in color, absorption, and angle of extinction. It does not agree with any of the alkalic series described by Brögger.[a] It may be that, although of alkalic type, the preponderance of potash over soda in the magma has had some effect in producing its novel characters. Unfortunately want of time and material have prevented the writer from investigating it chemically.

BOROLANOSE (SYENITE) OF PALISADE BUTTE.

As mentioned in the geologic description, the upper part of Palisade Butte is composed of a rock which is much lighter and more feld-

[a] Grorudit-Tinguait Serie, 1894, p. 27.

spathic than the shonkinose or shonkinite of the main lower portion. There is a gradation between the two, but the top is of distinctly syenitic character.

Megascopically the rock is medium granular, of a light-brown color, and dotted with augite. In the section the same minerals are seen as described under shonkinose—greenish augite, iron ore, apatite, alkali feldspars, and zeolites. The feldspars are in lath-like forms, which often radiate and produce rough spherulitic clusters. All the interspaces between them are filled with masses of a fibrous zeolite, which is largely natrolite. Probably nephelite or some other lenad (feldspathoid) mineral was originally present. The rock is not fresh enough to warrant more extended study, but an analysis of it was made to determine its systematic position and for purposes of magmatic comparison. This analysis is given under II of the preceding table. In regard to classification in prevailing systems, it has a position similar to the rock of Middle Peak; it could be classified as a basic syenite, though if all the zeolitic areas represent a former feldspathoid mineral, such as sodalite, it would probably fall into the nephelite-syenite family.

In the new system of classification the analysis can be calculated into a norm composed of the following standard minerals:

Or	44.48	
Ab	9.43	
An	8.03	73.76
Ne	11.03	
No	.71	
Di	10.20	
Ol	2.19	
Mt	5.34	20.93
Il	1.52	
Ap	1.68	
Rest	5.45	
Total	100.14	

Class, $\frac{\text{Sal.}}{\text{Fem.}}=\frac{73.76}{20.93}=2.6=$ II, dosalane.

Order, $\frac{L}{F}=\frac{11.79}{61.97}=1.9=$ lendofelic $=6$, norgare.

Rang, $\frac{Na_2O'+K_2O'}{CaO'}=\frac{140}{29}=4.9=$ domalkalic $=2$, essexase.

Subrang, $\frac{K_2O'}{Na_2O'}=\frac{80}{60}=1.3=$ sodipotassic $=3$, borolanose.

BOROLANOSE (SYENITE) OF SHONKIN SAG LACCOLITH.

What has been said above in regard to the light-colored rock of Palisade Butte applies well to this rock in a general way. The light-colored, grayish, moderately granular rock is dotted with considerable augite and less biotite.

In the section it is seen to be composed of apatite in small, pale violet-brown crystals, some iron ore, a few scattered olivines, some biotite in long foils of a dark-brown color and strongly pleochroic, a good deal of augite, not very well crystalized, pale brown in color and with good cleavage, a large amount of alkali feldspar greatly zeolitized, and some nephelite, which is fresher than the feldspar. The nephelite and feldspar are commonly intergrown in a poikilitic manner.

The rock is too much altered by zeolitization to warrant more extended description or a complete analysis, but to determine its affinities and for the purpose of comparing it with the associated shonkinose for reasons given in the chapter on the petrology, Doctor Hillebrand made a partial analysis, which is given under III of the preceding table. From this it will be seen that it closely resembles the rock of Palisade Butte just mentioned and also that of Middle Peak, both showing the characteristic high lime and potash of the Highwood magmas. As to systematic position in prevailing systems, it is a little difficult, in view of the zeolitization, to say whether this rock should be esteemed a basic member of the syenite group with accessory nephelite or a member of the nephelite-syenite family; probably it belongs in the latter and near the covite of Washington.

In the new system the analysis is sufficiently complete to calculate the norm and determine its position, which have been done as follows:

Or	49.48	76.01
Lc	.87	
Ne	16.76	
An	8.90	
Di	10.78	18.76
Ol	.83	
Mt	5.57	
Il	.91	
Ap	.67	
Rest	3.53	
Total	98.30	

Class, $\frac{\text{Sal.}}{\text{Fem.}}=\frac{76.01}{18.76}=4.0=$II, dosalane.

Order, $\frac{L}{F}=\frac{17.63}{58.38}=0.30=$lendofelic$=6$, norgare.

Rang, $\frac{K_2O'+Na_2O'}{CaO'}=\frac{150}{32}=4.6=$domalkalic$=2$, essexase.

Subrang, $\frac{K_2O'}{Na_2O'}=\frac{91}{59}=1.5=$sodipotassic$=3$, borolanose.

In making this calculation it has been assumed, from what is known of the mineral components of the rock, and the chemical character of the Highwood rocks in general, that 0.50 per cent of TiO_2 and 0.30 per cent of P_2O_5 are present, and a corresponding amount has been deducted from the Al_2O_3. While this is probably not absolutely correct, it is certainly more nearly correct than it would have been to have left these oxides out of account entirely. The result shows that the rock, like those of Middle Peak and Palisade Butte, is borolanose, where it evidently belongs. Considering its texture, it is, then, granoborolanose.

SHONKINOSE (SHONKINITE) OF SQUARE BUTTE.

The rock composing the dark-colored lower and outer mantle of Square Butte has already become well known as the original type of shonkinite, and for convenience and completeness the original description is summarized here.

Megascopic characters.—The shonkinose of Square Butte is a dark, coarse-grained, rather crumbly rock, which is mottled by the contrast between the black augite and the light-colored feldspathic material. The augites are greenish black, columnar, well formed, and average about 30 mm. in length, being found occasionally three times as large.

Considerable biotite is seen with bronze-lustered cleavage faces, which may be 1 or 2 cm. across, with irregular borders, and composed of smaller biotites in parallel growths which inclose poikilitically the other minerals. Filling the interspaces are the white feldspathic minerals. Augite is the most predominant mineral and makes up half the bulk of the rock.

Microscopic characters.—The microscope shows the following minerals: Apatite, iron ore, olivine, biotite, augite, albite, soda microcline, orthoclase, sodalite, nephelite, cancrinite, and zeolites.

Apatite is the oldest mineral and occurs in short, stout prisms. At times it is a pale red or violet brown and nonpleochroic. Other crystals are filled in the interior with a dusty pigment and are pleochroic; ε=pale steel-blue, ω=pale leather-brown. The prisms attain a length of 0.5 mm.

Olivine has its usual characters; it is generally fresh and colorless, but at times has a reddish ferruginous border that may be an alteration into iddingsite. In thicker sections some crystals have a faint pleochroism in tones of yellow and white.

Biotite is strongly pleochroic, deep umber-brown, and pale brownish-orange. The extinction is parallel to the cleavage. Thin plates have a small opening of the cross that shows it to be meroxene. Where olivine touches orthoclase there is usually a reaction band between them of a deep-green biotite, which has very little pleochroism or absorption.

Pyroxene occurs in good crystals and, owing to the ease with which they may be detached from the matrix, excellent material can be obtained for study. Measurements on the goniometer show the following forms: *a* (100), *b* (010), *m* (110), and *s* (111). The pyroxene is somewhat tabular on *a* (100). The crystals were crushed, sifted, and separated by the silver-thallium nitrate fluid, and material of great purity obtained in this way was subjected to chemical analysis with the following results:

Analysis of pyroxene in shonkinose of Square Butte.

SiO_2	49.42
TiO_2	.55
Al_2O_3	4.28
Fe_2O_3	2.86
FeO	5.56
MgO	13.58
CaO	22.35
MnO	.10
Na_2O	1.04
K_2O	.38
H_2O	.09
Total	100.21

A consideration of this analysis shows that the mineral has almost exactly this composition: $13\,Ca\,(MgFe)\,Si_2O_6 + 2\,(Na_2R'')\,(AlFe)_2\,SiO_6$.

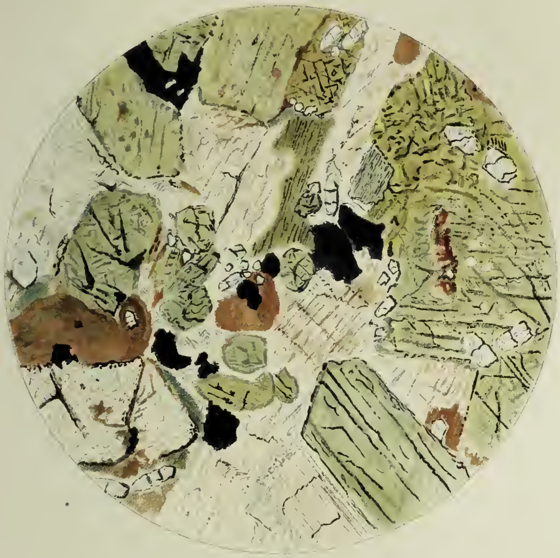
PLATE VII.

PLATE VII.

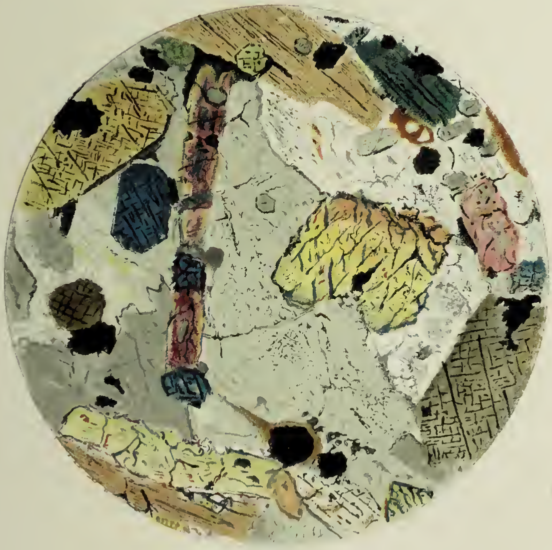
SHONKINOSE OF SQUARE BUTTE.

A. Shonkinose, Square Butte, Highwood Mountains, Montana: 18 diameters: polarized light; nicols uncrossed. Actual field, 4 mm. Apatite, iron ore, olivine, biotite, pyroxene, anorthoclase, orthoclase.

B. Shonkinose, Square Butte; 18 diameters; polarized light; nicols crossed. Actual field, 4 mm. Iron ore, apatite, biotite, augite, and orthoclase.



(A)



(B)

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SHONKINOSE OF SQUARE BUTTE

It is interesting to observe that if the analysis of this augite should be considered that of a rock, and the norm calculated, the augite would be composed of the following mineral molecules:

Calculated mineral composition of augite.

Leucite	1.74
Nephelite	4.83
Anorthite	5.84
Diopside	73.80
Akermanite	4.44
Olivine	3.81
Magnetite	4.18
Ilmenite	.91
Rest	.19
Total	99.74

In a general way this shows that the augite is greatly influenced in composition by the magma in which it is formed. This fact becomes more striking when seen in this way than by a bare comparison of analyses. It will be useful, also, to observe this calculation in making the comparison between the norm and mode of the new classification.

In thin section the augite is of a dark-green color with an olive tone, good cleavage, and occasional inclusions of iron ore. Orthoclase is the dominant feldspar. It is fresh and generally xenomorphic, occurs sometimes in rude columnar shapes, and contains inclusions of glass crystallographically arranged. The angle of the optic axes is variable, being usually small, sometimes nearly zero. In places the augite contains patches of intergrown soda microcline.

Albite is present in small amount, as shown by the specific gravity separation between 2.61 and 2.60. Qualitative analysis shows that the mineral is free from lime.

Nephelite has been found in the specific gravity separates and has been proved to be present in recent sections. It fills small interspaces, is commonly zeolitized, and the rock contains only a small amount of it.

Cancrinite was not definitely proved to be present in the sections, but was found and tested chemically in the products separated by heavy fluids.

Sodalite also occurs as an accessory mineral. It is seen occasionally in the section as a limpid isotropic filling of interspaces, but it is often zeolitized.

Natrolite occurs in fibrous patches and bundles secondary after feldspar, nephelite, and sodalite. The appearance of the rock in thin section is shown in Pl. VII, which also illustrates in a general way the character of the minerals in the Highwood rocks with femic norms.

Chemical composition.—The chemical composition of this rock is seen in the table below. Its characteristic features are the low silica and alumina, large amount of ferromagnesian oxides and lime, and the predominance of potash over soda.

Analyses of shonkinose and related rocks.

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.
SiO_2	46.73	50.00	48.98	47.88	48.05	50.15	52.09	0.779
Al_2O_3	10.05	9.87	12.29	12.10	13.94	15.86	11.93	.098
Fe_2O_3	3.53	3.46	2.88	3.53	2.67	2.44	1.84	.022
FeO	8.20	5.01	5.77	4.80	5.98	5.39	7.11	.114
MgO	9.27	8.31	9.19	8.64	7.81	5.30	12.48	.232
CaO	13 [illegible]2	11.92	9.65	9.35	7.25	8.40	7.84	.236
Na_2O	1.81	2.41	2.22	2.94	2.72	4.13	2.04	.029
K_2O	3.76	5.02	4.96	5.61	6.56	5.00	3.01	.040
H_2O+	1.24	1.16	.56	1.52	1.66	1.50	.35	------
H_2O-	--------	.17	.26	.70	-------	-------	--------	------
CO_2	--------	.31	-------	.12	-------	-------	.16	------
TiO_2	.78	.73	1.44	.77	1.10	1.00	.73	.010
P_2O_5	1.51	.81	.98	1.11	1.15	.86	.34	.011
SO_3	--------	.02	-------	None.	-------	-------	--------	------
Cl	.18	.03	-------	Trace.	-------	-------	Trace.	.003
Cr_2O_3	--------	.11	Trace.	.04	-------	-------	.10	------
NiO	--------	.07	-------	Trace.	-------	-------	.07	------
MnO	.28	Trace.	.08	.15	-------	-------	.15	------
BaO	?	.32	.43	.46	-------	-------	?	------
SrO	?	.07	.08	.13	-------	-------	?	------
Total	100.56	100.01	99.99	99.99	98.89	100.03	100.24	------
	.04	.08	.08	-------	-------	-------	--------	------
	100.52	99.93	99.91	-------	-------	-------	--------	------

I. Shonkinose (shonkinite) from Square Butte. L. V. Pirsson, analyst. (MgO corrected.)

II. Montanose (shonkinite) from Bearpaw Mountains. H. N. Stokes, analyst. Weed and Pirsson, Am. Jour. Sci., 4th ser., vol. 1, 1896, p. 360 (includes Fl.=.16).

III. Shonkinose (shonkinite) from Yogo Peak, Montana. W. F. Hillebrand, analyst. Weed and Pirsson, Am. Jour. Sci., 3d series, vol. 50, 1895, p. 474.

IV. Montanose (shonkinite) from Shonkin Sag laccolith. W. F. Hillebrand, analyst (includes S=.03; ZrO_2=.03).

V. Shonkinose (shonkinite) from Maros Peak, Borneo. Doctor Hinden, analyst. C. Schmidt in Sarasin's Celebes, vol. 4, 1901, p. 23.

VI. Shonkinose (shonkinite) from Maros Peak, Borneo. Doctor Hinden, analyst. C. Schmidt in Sarasin's Celebes, vol. 4, 1901, p. 23.

VII. Kentallenose (kentallenite) from Glen Shira, Argyllshire, Scotland. W. Pollard, analyst. Hill and Kynaston, Quart. Jour. Geol. Soc., vol. 56, 1900, p. 537.

These features are found in similar rocks from other Montana localities, as has been previously pointed out. As at Square Butte, they are also border differentiates of a single intruded mass. Its close similarity to montanose, described in a following section, is seen by comparing the analyses (I and IV of above table). The chief difference is that the montanose is considerably higher in alkalies and lower in ferromagnesian oxides. A closely related rock has recently been described by Schmidt from the island of Borneo under the name of shonkinite. It consists of augite, biotite, olivine, orthoclase, labradorite, with accessory apatite, iron ore, nephelite, and sodalite. Analyses of two specimens are given under V and VI. They closely resemble III, and the considerable amount of alkalies shows that they would fall near the subrang with the montanose, described later.[a]

In his work on the Monzoni rocks, Brögger[b] quoted an analysis of Lemburg's of a "pyroxenite" with large crystals of orthoclase, and pointed out the resemblance of these types to shonkinite. In his recent interesting study of the rocks of this region, Doelter[c] states that shonkinite occurs among them, but the type described is said to contain considerable plagioclase, which Romberg[d] calls attention to. The latter also states (p. 37) that shonkinite occurs on the Mulatto. Until more detailed studies and chemical analyses of these rocks have been made it will be impossible to form any definite opinion as to where they belong.

It is evident that while essexite, shonkinite, theralite, and alkalic pyroxenites all possess clear-cut and definite characters, there are many intermediate types whose classification in the older systems will be entirely a matter of opinion. So, for example, Hill and Kynaston have described, under the name of kentallenite, a rock consisting of essential olivine and augite with orthoclase and plagioclase in varying proportions. Its analysis is shown under VII of the table. The close chemical similarity to shonkinite is easily seen. In the new system of classification it has, however, a distinct place of its own.

Mineral composition or mode.—By study of the thin sections, with comparison of the chemical analysis and the powders yielded by the

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[a] A calculation of the norm from analysis V gives the following results:

Or	38.92	57.55
An	5.28	
Ne	13.35	
Di	19.00	40.12
Ol	12.36	
Mt	3.94	
Il	2.13	
Ap	2.69	
H_2O	1.66	
Total	99.33	

Class, $\frac{\text{Sal.}}{\text{Fem.}}=\frac{57.55}{40.12}=1.4=$ III, salfemane.

Order, $\frac{L}{F}=\frac{13.35}{44.20}=.30=$ lendofelic $=6$, portugare.

Rang, $\frac{Na_2O'+K_2O'}{CaO'}=\frac{117}{19}=$ domalkalic $=2$, monchiquase.

Subrang, $\frac{K_2O'}{Na_2O'}=\frac{70}{47}=1.49=$ sodipotassic $=3$, shonkinose.

[b] Triad. Erup. Predazzo, 1896, p. 67.

[c] Tschermak, Min. Mitt., vol. 21, 1902, pp. 100 and 103.

[d] Sitzb. k. Preuss. Akad. Wiss. Berlin., Phys., Mat., Kl., vols. 30, 32, 1902, pp. 675, 731.

heavy liquids, it may be calculated that an average specimen of the Square Butte shonkinose would have this mineral composition:

Mineral composition or mode of shonkinose of Square Butte.

Alkalic feldspar	20
Nephelite	5
Sodalite	1
Augite	46
Olivine	10
Biotite	8
Iron ore	6
Apatite	4
Total	100

Classification in the new system.—The calculation of the norm of the Square Butte rock and its position in the new system are shown in the following table:

Calculation of the norm of shonkinose.

	Analysis.	Molecular ratio.	Or.	Ab.	Ne.	So.	An.	Di.	Ol.	Mt.	Il.	Ap.
SiO_2	46.73	0.779	240	18	44	6	60	338	72			
Al_2O_3	10.05	.098	40	3	22	3	30					
Fe_2O_3	3.53	.022								22		
FeO	8.20	.114						44	38	22	10	
MgO	9.27	.232						125	107			
CaO	13.22	.236					30	169				37
Na_2O	1.81	.029		3	22	4						
K_2O	3.76	.040	40									
TiO_2	.78	.010									10	
P_2O_5	1.51	.011										11
Cl_2	.18	.003				1						2
Rest	1.52											
Total	100.56		40	3	22	1	30	169	72	22	10	11

Or	22.24	
Ab	1.57	
An	8.34	39.37
Ne	6.25	
So	.97	
Di	37.91	
Ol	11.36	
Mt	5.10	59.59
Il	1.52	
Ap	3.70	
Rest	1.52	
Total	100.48	

Class, $\frac{\text{Sal.}}{\text{Fem.}}=\frac{39.37}{59.59}=.66$=III, salfemane near dofemane.

Order, $\frac{\text{L.}}{\text{F.}}=\frac{7.22}{32.15}=.22$=lendofelic=6, portugare.

Rang, $\frac{Na_2O'+K_2O'}{CaO'}=\frac{69}{30}=2.3$=domalkalic=2, monchiquase.

Subrang, $\frac{K_2O'}{Na_2O'}=\frac{40}{29}=1.4$=sodipotassic=3, shonkinose.

Grad, $\frac{P+O}{M}=\frac{49.27}{6.62}=7.4$=perpolic=1, shonkinate.

Subgrad, $\frac{(MgFe)O+CaO''}{(K\,Na)_2O''}=\frac{483}{0}$=permirlic=1, shonkinote.

In comparing the norm with the mode it is seen that in the norm there is about 8 per cent of anorthite, which in the mode has gone almost entirely into the augite, and, conversely, about 8 per cent of biotite in the rock resolves itself in the norm into olivine and feldspathic minerals.

This biotite is thus a varietal mineral and produces a model variety of the normative rock. The texture is granular, and the type may thus be termed biotitic grano-shonkinose.

SHONKINOSE OF OTHER HIGHWOOD LOCALITIES.

Besides the occurrence at Square Butte, this rock is found in Palisade Butte, in the smaller laccolith in the Shonkin Sag, in the great stock at the head of Shonkin Creek, and in several smaller masses and intruded sheets, as described under the discussion of the geology. There is some variation among the rocks, both in texture and in the relative proportion of minerals. The Shonkin stock varieties are apt to be coarser grained and more xenomorphic than the Square Butte type and to have much less biotite; but aside from this the types do not need any special mention and are covered by the foregoing description. One exception to this, however, is the rock closely related to shonkinose in which leucite is an essential component. This is described in the following section:

LEUCITE-SHONKINOSE (LEUCITE-SHONKINITE) OF EAST PEAK.

Introductory.—The study of the material collected by Mr. Weed at the Shonkin stock shows some variability in the proportions of the salic and femic minerals. These variations are not, however, very great and never extreme. In the hand specimens the salic and femic components appear to be similar throughout the series, but under the microscope the salic are found to be sometimes chiefly alkalic feldspars, making the rock shonkinite (shonkinose), and sometimes leucite, forming missourite (grad missourate). There are, moreover, transitional types between these two, the ferromagnesian minerals remaining the same, while the light or feldspathic ones are mixtures in various proportions of alkalic feldspars and leucite. Small amounts of nephelite, sodalite, and zeolites may also be present. In addition to these occurrences at the Shonkin stock, it has been found that the rock composing the mass of the East Peak stock at the head of Davis Creek is of this type and it was studied to ascertain its relations to the normal shonkinose.

Megascopic characters.—The occurrence and geologic relations of this rock mass have been described in a previous chapter. In the specimen the rock is a dark gray of medium to fine grain, and the automorphic character of the augites tends to give it a somewhat porphyritic appearance. In this it differs somewhat from the coarser and massive-looking rocks of Square Butte, Shonkin Creek, etc. In addition to the augite, occasional grains of olivine are seen. The material forming the great cliff and the huge talus masses at its foot is not so fresh as the outcrops on the little ridge or foothill to the south at the border of the intrusion. The material analyzed came from this southern edge, where the rock is somewhat coarser grained.

Microscopic characters.—In thin section the rock is seen to be made up of the usual minerals of shonkinose: Augite, iron ore, apatite, olivine, biotite, with alkalic feldspars and isotropic minerals. The femic minerals are of the character already described under shonkinose. The iron ore, which is not very abundant, is in small, round, dotted grains. The augite, in large, well-formed crystals, is like that described under shonkinose. There is some olivine, which is fresh, and, unlike that in shonkinose, it is almost never surrounded by coronæ of biotite. The absence of biotite in the rock is, in fact, a noticeable feature and is to be correlated with the occurrence of leucite. This mutual relation between olivine, leucite (and its feldspar equivalent, orthoclase), and biotite is well known, and its significance in these rocks has already been shown by the writer.[a]

The alkalic feldspars are present in small laths and larger shapeless masses which often show Carlsbad twinning. In the material from the cliff and talus (Nos. 757 and 758) a curious alteration of these feldspars was noticed. When fresh they show no zonal structure, but in these cases a process of zeolitization has gone on, so that sections parallel to 010 show a marked zonal structure, alternate bands polarizing in yellow tones, while those between are the gray color usual to these feldspars in the average thin section. It appears that some zones are much richer in soda than others, and these have become converted into natrolite, which has a considerably higher birefringence than the soda orthoclase which composes the intervening layers, thus producing the effect mentioned. The alkalic feldspars are also somewhat kaolinized in some of these examples.

The leucite appears abundantly in certain areas. Between crossed nicols these areas appear homogeneous, isotropic for the most part, but here and there show the faint cross-banded twinning so characteristic of larger leucites. In plain light the areas are compound and made up of grains, as is shown by their outlines, cracks, and the zonal arrangement of fine black, dotted inclusions, a well-known feature in leucite. It is to be noted, however, that not all of the areas show these inclusions or cross twinning.

There are also some areas which in plain light show all the character of the leucite, but between crossed nicols break up into a fine mosaic of grains of low polarization. These are undoubtedly altered leucites, or pseudoleucites, consisting now of feldspar, nephelite, and zeolite granules. In the material from the cliff (757) there are no real

[a] Bull. Geol. Soc. America, vol. 6, 1895, p. 409.

leucites, but the mode of occurrence, arrangement of inclusions, etc., show that they were once present as in the rock of the south boundary (760).

Chemical composition of white components.—In order to investigate these white components a separation was made with heavy fluids and various crops obtained all the way from 2.60 to 2.25, a result which might naturally be expected in mixtures of alkalic feldspars, leucite, and zeolites. It was intended to analyze the material having a specific gravity of 2.45, the specific gravity of leucite, but unfortunately this material was lost, and the next below, at 2.38, was taken. Under the microscope this was found to be very pure, consisting of isotropic grains. About 0.2 gram was available for the analysis, which had, therefore, to be made with great care. The results were as follows:

Analysis of white component of leucite-shonkinose.

	I.	II.
SiO_2	56.00	0.933
Al_2O_3	21.27	.209
Fe_2O_3	Trace.	
CaO	.33	.005
Na_2O	5.16	.084
K_2O	10.85	.116
H_2O	6.89	.383
SO_3	None.	
Cl	None.	
MnO	Trace.	
Total	100.50	

By using the molecular ratios given in the last column it can be easily calculated that this material consists of a mixture of equal parts, by weight, of leucite and analcite (lc., 50.58; anc., 49.42). If the specific gravity of leucite be taken as 2.45 and that of analcite as 2.30, a mixture of equal parts of the two would have a specific gravity of 2.38, that of the powder analyzed.

Occurrence of analcite.—The presence of the analcite thus proved is of interest. It could not be detected in the ordinary way with the microscope on account of the leucite, both, of course, appearing as isotropic grains.

The question at once arises whether this analcite is primary or not. A study of the sections affords no direct evidence on this point, and the question is similar to the one raised in regard to the monchiquose (analcite-basalt), discussed elsewhere in this bulletin.

It should be noted, however, that while some of the material from this locality is considerably altered and zeolitized the specimen (760) from the southern edge under examination shows nothing of this, and except for the presence of analcite and some pseudoleucites, or what are thought to be such, the rock is fresh and unaltered. The femic minerals are unchanged, and in the case of the olivine this is to be noted. So far as these facts afford evidence, the analcite does not appear to be due to secondary alteration. It is not logical to say that the analcite is secondary and, therefore, the rock must be altered, and that because the rock is altered the analcite must be therefore a product of alteration. The proofs of its secondary nature which are often advanced consist of just this reasoning in a circle. All that can be said in this instance is that the analcite appears like a primary mineral, and that the arguments for and against its primary nature are the same as those discussed under the head of the dikes of monchiquose (analcite-basalt). Some additional indirect evidence will be presented in a subsequent paragraph devoted to the calculation and discussion of the norm.

Chemical composition of the rock.—An analysis of this rock (760) has been made under the writer's direction by Mr. E. B. Hurlburt, with the results shown in I of the table on the opposite page.

For purposes of comparison two analyses of typical shonkinose, the original one from Square Butte and the one from Yogo Peak, are added, and it will be seen that they are all of the same general character, but that the East Peak type has higher alkalies and somewhat lower bivalent oxides. This low silica with considerable alkalies and dominant potash has caused the formation of leucite along with the alkalic feldspars. Under VIII is given the analysis of "missourite," which has no feldspar, but whose potash is all in leucite. The silica in this is the same as in the "shonkinite" of Square Butte, but the latter has lower alkalies and therefore all feldspar and no leucite. Thus, from "shonkinite" through leucite-"shonkinite" to "missourite" there is a regularly graded series from potash feldspar through potash feldspar and leucite to leucite alone, depending on the relative proportions of silica and potash. When it is recalled that orthoclase=K_2O Al_2O_3 $6SiO_2$ and leucite=K_2O Al_2O_3 $4SiO_2$, this relation is easily understood. The soda in part follows the potash into the feldspar and in part, having a lesser affinity for silica, it forms lenad (feldspathoid) minerals throughout the series, which, if conditions of formation were favorable, might be hydrated, i. e., analcite.

The most nearly related type found by the writer outside of the Highwood area is a shonkinose ("leucitophyre") from Persia, whose analysis, by Steinecke, is shown under IV. The chemical correspondence of these two rocks from such widely separated regions is remarkable; the only difference is that the Persian type contains a little less iron and a little more lime.

The correspondence between leucite-shonkinose and the nearly related montanose ("shonkinite") from the Shonkin Sag laccolith is

Analyses of leucite-shonkinose and related rocks.

	I	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.
SiO_2	49.59	46.73	48.98	49.65	47.88	46.04	47.98	46.06	0.827
Al_2O_3	14.51	10.05	12.29	14.39	12.10	12.23	13.34	10.01	.142
Fe_2O_3	3.51	3.53	2.88	4.21	3.53	3.86	4.09	3.17	.022
FeO	5.53	8.20	5.77	3.46	4.80	4.60	4.24	5.61	.076
MgO	6.17	9.25	9.19	6.27	8.64	10.38	7.01	14.74	.154
CaO	9.04	13.22	9.65	10.12	9.35	8.97	9.32	10.55	.160
Na_2O	3.52	1.81	2.22	3.21	2.94	2.42	3.51	1.31	.056
K_2O	5.60	3.76	4.96	5.46	5.61	5.77	5.00	5.14	.060
H_2O+	1.95	1.24	.56	2.37	1.52	2.87	2.10	1.44	-----
H_2O-	-------	-------	.26	-------	.70	-------	-------	-------	-----
CO_2	-------	-------	-------	-------	.12	-------	1.24	-------	-----
TiO_2	.36	.78	1.44	(?)	.77	.64	.58	.73	.004
P_2O_5	.15	1.51	.98	.79	1.11	1.14	1.03	.21	.001
SO_3	.02	-------	-------	-------	None.	Tr.	Tr.	.05	-----
Cl	.13	.18	-------	-------	Tr.	.11	.21	.03	-----
Cr_2O_3	-------	-------	Tr.	-------	.04	-------	-------	-------	-----
Fl	-------	-------	.22	-------	.05	-------	-------	-------	-----
MnO	Tr.	.28	.08	.25	.15	Tr.	Tr.	Tr.	-----
BaO	.49	(?)	.43	(?)	.46	.48	.50	.32	.003
SrO	.21	(?)	.08	(?)	.13	.25	.14	.20	-----
	100.78	100.56	99.99	100.19	99.99	99.76	100.29	99.57	-----
O=Cl	.03	.04	.10	-------	.02	.03	.07	.01	-----
Total	100.75	100.52	99.89	100.19	99.97	99.73	100.22	99.56	-----

I. Leucite-shonkinose (leucite-shonkinite) from East Peak, Highwood Mountains, Montana. E. B. Hurlburt, analyst.

II. Shonkinose (shonkinite) from Square Butte, Highwood Mountains, Montana. L.V. Pirsson, analyst. Bull. Geol. Soc. America, vol. 6, 1895, p. 414.

III. Shonkinose (shonkinite) from Yogo Peak, Little Belt Mountains, Montana. W. F. Hillebrand, analyst. Am. Jour. Sci., 3d series, vol. 50, 1895, p. 474.

IV. Shonkinose (leucitophyre) from near Khoi, Persia. J. Steinecke, analyst. Zeit. Naturw. Halle, vol. 6, 1887, p. 12.

V. Montanose (shonkinite) from Shonkin Sag laccolith, Highwood Mountains, Montana. W. F. Hillebrand, analyst. Am. Jour. Sci., 4th series, vol. 12, 1901, p. 14.

VI. Biotite-cascadose (mica-basalt) from Arrow Peak dike, Highwood Mountains, Montana. H. W. Foote, analyst.

VII. Shonkinose (leucite-basalt) from Pinewood Peak flow, Highwood Mountains, Montana. H. W. Foote, analyst.

VIII. Albanose (missourite) from head of Shonkin Creek, Highwood Mountains, Montana. E. B. Hurlburt, analyst. Am. Jour. Sci., 4th series, vol, 2, 1896, p. 321.

IX. Molecular proportions of No. I.

shown by a comparison of the analyses I and V, respectively, which show how delicate is the balance which determines the formation of orthoclase and biotite instead of orthoclase with leucite and olivine.

Under VI and VII are analyses of dikes and flows of the region, and comparison may be made not only with the leucite-shonkinose but also of the normal shonkinose with similar magmas of the area which have a different method of occurrence.

Mineral composition or mode.—On account of the mingled analcite and leucite the mineral composition can not be accurately computed, but the relation of the salic to the femic minerals is expressed very closely in the norm, which represents also in a general way the femic minerals. If the leucite pseudomorph areas are reckoned as leucite, observation shows that the amount of leucite to feldspar is about 7 to 3; but a considerable proportion of what is called leucite—perhaps a third or more—is really analcite.

Classification in the new system.—The position of the rock in the new system is shown in the following computation of its analysis:

Calculation of the norm of leucite-shonkinose.

	Analysis.	Molecular ratio.	Or.	Lc.	Ab.	Ne.	So.	An.	Di.	Ol.	Mt.	Il.	Ap.
SiO_2	49.59	0.826	360	----	6	94	12	56	260	36	----	----	----
Al_2O_3	14.51	.142	60	----	1	47	6	28	----	----	----	----	----
Fe_2O_3	3.51	.022	----	----	----	----	----	----	----	----	22	----	----
FeO	5.53	.076	----	----	----	----	----	----	31	18	22	5	----
MgO	6.17	.154	----	----	----	----	----	----	99	55	----	----	----
CaO	9.04	.161	----	----	----	----	----	28	130	----	----	----	3
Na_2O	3.52	.056	----	----	1	47	8	----	----	----	----	----	----
K_2O	5.60	.060	60	----	----	----	----	----	----	----	----	----	----
TiO_2	.36	.005	----	----	----	----	----	----	----	----	----	5	----
P_2O_5	.15	.001	----	----	----	----	----	----	----	----	----	----	1
Cl_2	.13	.002	----	----	----	----	2	----	----	----	----	----	----
Rest	2.67	----	----	----	----	----	----	----	----	----	----	----	----
Total	100.78	----	60	----	1	47	2	28	130	36	22	5	1

Or	33.36	56.94
Ab	.52	
An	7.78	
Ne	13.35	
So	1.93	
Di	29.07	40.95
Ol	5.68	
Mt	5.10	
Il	.76	
Ap	.34	
Rest	2.67	
Total	100.56	

Class, $\frac{\text{Sal.}}{\text{Fem.}}=\frac{56.94}{40.95}=1.2=$ III, salfemane.

Order, $\frac{L}{F}=\frac{15.28}{41.66}=0.36=$ lendofelic $=6$, portugare.

Rang, $\frac{Na_2O'+K_2O'}{CaO'}=\frac{116}{28}=4.1=$ domalkalic $=2$, monchiquase.

Subrang, $\frac{K_2O'}{Na_2O'}=\frac{60}{56}=1.0=$ sodipotassic $=3$, shonkinose.

The calculation shows the rock to be a normal shonkinose with orthoclase and nephelite and no leucite. The reason of this is apparent when one considers that nephelite has been calculated instead of analcite. The formula of nephelite is $Na_2O\ Al_2O_3\ 2SiO_2$ and that of analcite is $Na_2O\ Al_2O_3\ 4SiO_2\ 2H_2O$. The formation of theoretical nephelite consequently releases enough silica to convert what would otherwise be leucite into orthoclase. This is a strong argument in favor of the primary nature of the analcite. If the rock had crystallized anhydrously, we should have expected the formation of the minerals shown in the norm. Considering our knowledge of the crystallization of molten magmas and the affinities of the oxides, they could not have been different from these. If the analcite is secondary, the aqueous solutions have taken silica from orthoclase, reducing it to leucite and converting nephelite into analcite. In this case the leucite is also secondary. If we reject this, we must fall back on the view that aqueous solutions carrying soda and silica have acted on the rock and presumably on leucite, have removed from a part of it a vast amount of potash and replaced it with soda, and have not attacked the other minerals, especially the olivine. The action thus becomes an entirely selective one. It would seem simpler to suppose that the water vapor originally present in the magma caused the formation of analcite, and thus indirectly also of leucite.

From what has been shown it is evident that this rock has an abnormative mode, and since it has a granular texture it should be termed a grano-leucite-sho[illegible]

Classification in prevailing [illegible]s.—As the white components of this rock consist chiefly of leucite [illegible] alkalic feldspar it was at first provisionally termed leucite-syenite, under which name the analysis was first published in Bulletin 148 of the United States Geological Survey. Considering, however, the relative amounts of light and dark minerals, its chemical composition, and its regional affinities, the name leucite-shonkinite would be much more appropriate.

MONTANOSE (SHONKINITE) OF SHONKIN SAG LACCOLITH.

Introductory.—In the rocks of the stocks and laccoliths the order portugare of the salfemanes in the new system of classification is represented in both the peralkalic and the domalkalic rangs, wyomingase and monchiquase. In subrangs it is the sodipotassic in both, and under monchiquase it is shonkinose. The rocks have been fully described and their positions shown in the foregoing section.

Under wyomingase, where the rocks are peralkalic, subrang 3 has received no name, and it is here proposed to describe a Highwood type which occurs within it and call this subrang montanose. This is the material forming the dark outer zone of the Shonkin Sag laccolith.

Under prevailing systems of classification, in which regard is paid only to the presence of certain minerals and none to their relative quantities, the difference between the relative amounts of the alkalic minerals in this type and the shonkinose last described would not be recognized, and both rocks would be classed under shonkinite.

Megascopic and microscopic characters.—In the hand specimen the rock is much like the former type, a dark-gray, medium- to coarse-grained mixture of salic and femic minerals. There is less automorphism in the femic minerals than in the Square Butte rock.

In thin sections there appear the same minerals as in shonkinose—iron ore, apatite, olivine, biotite, augite, alkalic feldspars, nephelite, sodalite, and some zeolites. The apatite and iron ore are similar; the fresh olivine is in the same way surrounded by biotite mantles, brown within and green without, where contact would be made with the orthoclase. The biotite is well crystallized and tends to form in long foils and have darker borders, as in minette; it recalls the biotite of theralite, but has parallel extinction. The augite in places has fine borders of a deeper green, from admixture of the ægirite molecule. There is present some soda microcline with very fine albite twinning which is partly zeolitized. The orthoclase is like that in shonkinose. Considerable nephelite is present, shown by its uniaxial negative cross and low birefringence; it is fresh, but often incloses hexagons of zeolitized sodalite. The texture, fabric, etc., are as in shonkinose.

Chemical composition.—The chemical composition of this rock is shown in a complete analysis by [illegible] Hillebrand; it has been given under shonkinose, but is r[illegible] the opposite page for the sake of convenience.

In Washington's[a] tables of analyses are found two other analyses which come under this subrang. One is of shonkinite of the Beaver Creek stock in the Bearpaw Mountains; the other differs in the presence of much ægirite as its dominant femic mineral, and one would naturally classify it under an entirely different grad and subgrad. It is interesting to note in connection with this analysis how ferrous iron plays the function usually filled by magnesia, while soda, in forming a femic mineral, does the same for lime.

The analysis of the Shonkin Sag montanose shows all the distinctive characters of the salfemic rocks of the Highwoods, and it is unnecessary to do more than point this out.

[a] Prof. Paper U. S. Geol. Survey No. 14, 1903, p. 338.

Analyses of montanose and related rocks.

	I.	II.	III.	IV.
SiO_2	47.88	50.00	48.90	0.796
Al_2O_3	12.10	9.87	7.85	.119
Fe_2O_3	3.53	3.46	11.46	.022
FeO	4.80	5.01	13.32	.067
MgO	8.64	11.92	.38	.216
CaO	9.35	8.31	1.95	.167
Na_2O	2.94	2.41	7.40	.047
K_2O	5.61	5.02	3.23	.060
H_2O+	1.52	1.16	1.80	
H_2O-	.70	.17		
CO_2	.12	.31		
TiO_2	.77	.73		.010
P_2O_5	1.11	.81		.008
SO_3	None.	.02		
Cl	Trace.	.08	.03	
Cr_2O_3	.04	.11		
NiO	Trace.	.07		
MnO	.15	Trace.	1.11	
BaO	.46	.32		
SrO	.13	.07		
Total	99.99	100.01	99.39	

I. Montanose (shonkinite) from Shonkin Sag laccolith, Highwood Mountains. W. F. Hillebrand, analyst (includes S.=.03, ZrO_2=.03, Fl.=.05, and V_2O_3=.04).

II. Montanose (shonkinite) from Beaver Creek, Bearpaw Mountains, Montana. H. N. Stokes, analyst (includes Fl.=.16). Am. Jour. Sci., 4th series, vol. 1, 1896, p. 360.

III. Montanose from Kangerdluarsuk, Greenland. C. Detlefson, analyst (includes ZrO_2=1.96). Rosenbusch, Elemente, p. 133, 1898.

IV. Molecular proportions of No. I.

Classification in the new system.—The position of the rock in the new system is shown in the following calculation of its norm and systematic position:

Calculation of the norm of montanose.

	Analysis.	Molecular ratio.	Or.	Ne.	An.	Di.	Ol.	Mt.	Il.	Ap.
SiO_2	47.88	0.796	360	94	24	258	61			
Al_2O_3	12.10	.119	60	47	12					
Fe_2O_3	3.53	.022						22		
FeO	4.80	.067				18	17	22	10	
MgO	8.64	.216				111	105			
CaO	9.35	.167			12	129				26
Na_2O	2.94	.047		47						
K_2O	5.61	.060	60							
TiO_2	.77	.010							10	
P_2O_5	1.11	.008								8
Rest	3.26									
Total	99.99									

Or	33.36	50.05
An	3.34	
Ne	13.35	
Di	28.44	46.83
Ol	9.08	
Mt	5.10	
Il	1.52	
Ap	2.69	
Rest	3.26	
Total	100.14	

Class, $\frac{\text{Sal.}}{\text{Fem.}}=\frac{50.05}{46.83}=1.0=$III, salfemane.

Order, $\frac{\text{L.}}{\text{F.}}=\frac{11.35}{36.70}=0.36=$lendofelic$=6$, portugare.

Rang, $\frac{Na_2O'+K_2O'}{CaO'}=\frac{107}{12}=9=$peralkalic$=1$, wyomingase.

Subrang, $\frac{K_2O'}{Na_2O'}=\frac{60}{47}=1.3=$sodipotassic$=3$, montanose.

Grad, $\frac{\text{P.+O.}}{\text{M.}}=\frac{37.52}{6.62}=5=2$, dopolic.

Subgrad, $\frac{(Mg\ Fe)O+CaO''}{(NaK)_2O''}=\frac{370}{0}=1$, permirlic.

In chemical composition this rock stands very near the center of the subrang, and it is therefore very nearly a typical analysis. That this is so may be seen if we assume exact center points and then from this reverse the ordinary process of calculation, obtaining the theoretical chemical composition and the corresponding norm for the assumed rock.

Calculation of chemical composition.

I.	II.	III.	Or.	Ab.	Ne.	Di.	Ol.	Mt.
SiO_2	50.8	0.846	342	54	96	282	72	
Al_2O_3	11.6	.114	57	9	48			
Fe_2O_3	6.5	.041						41
FeO	3.0	.041						41
MgO	11.4	.285				141	144	
CaO	7.9	.141				141		
Na_2O	3.5	.057		9	48			
K_2O	5.4	.057	57					
Total	100.1		57	9	48	141	72	41

Norm.

Or	31.7
Ab	4.7
Ne	13.5
Di	30.6
Ol	10.0
Mt	9.4
Total	99.9

Center points.

Class, $\frac{\text{Sal.}}{\text{Fem.}}=\frac{50}{50}=1.0=$III, salfemane.

Order, $\frac{\text{L.}}{\text{F.}}=0.37=6$, lendofelic.

Rang, $\frac{Na_2O'+K_2O'}{CaO'}=00=$I, peralkalic.

Subrang, $\frac{Na_2O}{K_2O}=1.0=3$, sodipotassic.

The calculated chemical composition given in column II of the above table is seen to be, in general, very close to the actual analysis previously given.

The mode or actual mineral composition of the rock differs from this theoretical norm in that some of the molecules which would otherwise have gone to making olivine and feldspathoid minerals have actually united to make about 10 per cent of biotite. On account of this biotite and because the texture is granular the rock should be termed "biotitic grano-montanose."

MISSOUROTE (MISSOURITE) OF THE SHONKIN STOCK.

Introductory.—This rock has been described in a previous paper by the author and Mr. Weed, who collected the material and gave an account of its mode of occurrence in the Shonkin stock. As the type filled a gap in the prevailing systems of classification and was the first recorded instance, so far as known to the writer, of an intrusive rock containing unaltered leucite, it has become widely known, and the name was adopted in petrographic nomenclature. In the new classification it occupies an interesting position, as will be shown, and in order to facilitate the discussion the essence of the former description and the chemical analyses are here repeated. The locality and mode of occurrence have been given in the description of the Shonkin stock.

Megascopic characters.—The rock appears dark gray, coarse grained, and resembles many basic massive rocks in appearance. In the specimen it is seen to be coarsely and evenly granular and to be composed of light and dark constituents, the proportion by bulk being about two of the light to three of the dark minerals. The separation by the heavy fluids shows, however, that by weight the white mineral forms only one-fifth to one-quarter of the whole. The distinction in color is strongly marked and gives the rock a mottled, mosaic-like appearance.

Upon examination the dark constituents may be distinguished as chiefly a greenish-black augite in columnar masses and aggregates which are never automorphic, and an occasional speck of a bronzy brown biotite of ill-defined outline or a grain of a deep-yellow olivine. Filling the interspaces between these dark minerals in formless masses is a very pale greenish-gray substance which is leucite. The average size of crystal grain varies from 2 to 5 mm, so that the rock is of coarse granular structure, and resembles most strikingly many coarse-grained gabbros.

Microscopic characters.—The thin section under the microscope shows the minerals present to be apatite, iron ore, olivine, augite, biotite, leucite, and some zeolitic products.

The apatite and iron ore, which are present rather rarely in moderate-sized grains, show nothing of especial interest beyond that they are found inclosed in the other minerals, and the biotite frequently incloses the iron ore.

The olivine is extremely fresh, unaltered in any way, and resembles the olivine of fresh gabbros. It contains great numbers of very fine glass and iron-ore inclusions. It never shows any crystal faces, but is in rounded, formless, anhedral grains which are frequently inclosed in biotite and augite.

The augite is of a pale-green color with a tone of brown; it is very fresh and clear, contains inclusions of ore and specks of biotite, and is entirely xenomorphic, though the orientation of the ore grains is at times zonal, thus indicating crystal planes. It has an excellent cleavage, and twinning bands pass through it in places; it does not show any pleochroism.

The biotite is strongly pleochroic between a deep umber-brown and a pale yellow-brown; it is also entirely xenomorphic, though apt to surround the other minerals in bands, especially the olivine and iron ore. It is particularly characteristic in such cases that it passes from brown into an olive-green variety which has a mottled, somewhat stringy, fibrous appearance. In these cases it appears as if the brown variety had suffered from some magmatic process; it does not seem to be due to any ordinary process of weathering.

The leucite also appears in formless masses filling the interspaces between other minerals. It is perfectly clear and free from all inclusions, except now and then a grain of the ferromagnesian minerals. Between crossed nicols it shows most beautifully the cross-banded twinning structure so characteristic of leucite. It is in general perfectly clear, limpid, and fresh, though in some areas, in delicate fringes along cracks and on the borders of grains, a low birefraction shows that processes of zeolitization have commenced.[a]

Chemical composition.—An analysis of the rock has been made by Mr. E. B. Hurlburt, with the following results:

Analyses of missourote and related rocks.

	I.	II.	III.	IV.	Ia.
SiO_2	46.06	47.28	46.73	44.35	0.767
Al_2O_3	10.01	11.56	10.05	10.20	.097
Fe_2O_3	3.17	3.52	3.53	13.50	.020
FeO	5.61	5.71	8.20		.078
MgO	14.74	13.17	9.27	12.31	.368
CaO	10.55	9.20	13.22	11.47	.188
Na_2O	1.31	2.73	1.81	3.37	.021
K_2O	5.14	2.17	3.76	4.42	.054
H_2O	1.44	2.96	1.24	(?)	.080
TiO_2	.73	.88	.78	(?)	.009
P_2O_5	.21	.59	1.51	(?)	
MnO	Trace.	.13	.28		
BaO	.32	(?)	(?)	(?)	
SrO	.20	(?)	(?)	(?)	
SO_3	.05		None.		
Cl	.03	.18	.18		
	99.57	100.08	100.56	99.62	
Cl=O	.01	.04	.04		
Total	99.56	100.04	100.52		

I. Missourote (missourite), from head of Shonkin Creek, Highwood Mountains, Montana. E. B. Hurlburt, analyst.

II. Camptonose (leucite-absarokite). J. E. Whitfield, analyst. Hague, Am. Jour. Sci., 3d series, vol. 38, 1889, p. 43. Iddings, Jour. Geol., vol. 3, 1895, p. 938.

III. Shonkinose (shonkinite) from Square Butte, Highwood Mountains. L. V. Pirsson, analyst. Bull. Geol. Soc. America, vol. 6, 1895, p. 414. MgO corrected.

IV. Leucite-basalt, from Bongsberg, by Pelm, Eifel. E. Hussak, analyst. Sitzb. K. Akad Wiss. Wien, vol. 77, pt. 1, 1878.

Ia. Molecular ratios of No. I.

[a] An analysis of it on material separated by heavy liquids gave—

SiO_2	54.46
Al_2O_3	22.24
Fe_2O_3	.68
CaO	.10
Na_2O	.70
K_2O	18.86
H_2O	2.29
Total	99.33

This analysis brings out strongly the leading characteristics of the rock—its very high lime, iron, and magnesia, which have compelled the formation of such quantities of pyroxene and olivine, and the predominance of potash over soda, which, with the low silica, has conditioned the formation of the leucite and prevented the forming of feldspar.

Mineral composition or mode.—Taking into account the ratios shown by the analysis, the separations by the heavy liquid, and the study of the section, the rock has approximately the following mineral composition:

Mineral composition or mode of missourote.

Iron ore	5
Augite	50
Olivine	15
Biotite	6
Leucite	16
Analcite	4
Zeolites	4
Total	100

This composition as originally calculated must be approximately correct, as Prof. F. W. Clarke informs the writer that on leaching the rock with ammonium chloride the following percentages were obtained in the extract:

	A.	B.
CaO	1.73	1.70
K_2O	4.09	3.74
Na_2O	.59	.64

This gives, on calculation into mineral molecules, leucite (K Al Si_2O_6), 18.24; analcite (Na AL $Si_2O_6H_2O$), 4.70.

As the rock itself varies somewhat this may be considered a very satisfactory agreement.

Classification in prevailing systems.—In the prevailing systems of classification this rock has a distinct place. It is the massive granular, plutonic representative of the leucite-basalts and bears the same relation to them that gabbro bears to common plagioclase-basalt or granite to rhyolite. For this reason it was given a distinct name of its own, missourite. The writer can not agree with the suggestion by Löwinson-Lessing[a] that leucite-gabbro would have been appropriate, for in the usage of petrographers this would have meant a gabbro—that is, a plagioclase rock—with additional leucite, and this

[a] Löwinson-Lessing, Studien ueber die Eruptivgesteine: Compte-rendu vii session Cong. Geol. Inter. Russ., 1897, p. 282.

would have been incorrect. This idea was thought of at the time and this name in consequence rejected.

Classification in the new system.—In the new system the rock occupies an interesting position, and one which, moreover, points a moral in regard to all systems of rock classification based on the inherent nature of the things classified. Its norm is determined from the following calculation:

Calculation of the norm of missourote.

	Analysis.	Molecular ratio.	Or.	Lc.	Ne.	An.	Di.	Ol.	Mt.	Il.	Ap.
SiO_2	46.06	0.767	36	192	42	46	324	127	----	----	----
Al_2O_3	10.01	.098	6	48	21	23	------	------	----	----	----
Fe_2O_3	3.17	.020	----	------	----	----	------	------	20	----	----
FeO	5.61	.078	----	------	----	----	19	30	20	9	----
MgO	14.74	.368	----	------	----	----	143	225	----	----	----
CaO	10.55	.188	----	------	----	23	162	------	----	----	3
Na_2O	1.31	.021	----	------	21	----	------	------	----	----	----
K_2O	5.14	.054	6	48	----	----	------	------	----	----	----
TiO_2	.73	.009	----	------	----	----	------	------	----	9	----
P_2O_5	.21	.001	----	------	----	----	------	------	----	----	1
Rest	2.04	--------	----	------	----	----	------	------	----	----	----
Total	99.57	--------	6	48	21	23	162	127	20	9	1

Or	3.34	36.60
An	6.39	
Lc	20.93	
Ne	5.94	
Di	35.60	60.76
Ol	18.81	
Mt	4.64	
Il	1.37	
Ap	.34	
Rest	2.04	
Total	99.40	

Class, $\frac{\text{Sal.}}{\text{Fem.}}=\frac{36.60}{60.76}=.601=$III, salfemane.

Order, $\frac{\text{L.}}{\text{F.}}=\frac{26.87}{9.73}=2.1=$dolenic$=8$, bohemare.

Rang, $\frac{Na_2O'+K_2O'}{CaO'}=\frac{75}{23}=3.2=$domalkalic$=2$, albanase.

Subrang, $\frac{K_2O'}{Na_2O'}=\frac{54}{21}=2.6=$dopotassic$=2$, albanose.

Grad, $\frac{P+O}{M}=\frac{54.41}{6.01}=9=$perpolic$=1$, missourate.

Subgrad, $\frac{(MgOFeO)+CaO''}{(K\ Na)_2O''}=\frac{608}{0}=$permirlic$=1$, missourote.

The rock is almost exactly on the dividing line between salfemane and dofemane, which is $\frac{\text{Sal}}{\text{Fem}}=\frac{3}{5}=.6$. If the BaO and SrO are taken into account—their amounts are given in the analysis on a preceding page—and they are reckoned in with the feldspars, where they clearly belong, the norm figures out—

Orthoclase	1.11	
Leucite	22.67	
Nephelite	5.94	36.40
Anorthite	5.28	
Hyalophane	1.40	
Diopside	36.68	
Olivine	18.60	
Magnetite	4.64	61.63
Ilmenite	1.37	
Apatite	.34	
Rest	1.52	
Total	99.55	

Class, $\frac{\text{Sal}}{\text{Fem}}=\frac{36.40}{61.63}=.590$=IV, dofemane.

Order, $\frac{\text{P+O}}{\text{M}}=\frac{55.28}{6.35}=8.9$=perpolic=1, hungarare.

Section, $\frac{\text{P}}{\text{O}}=\frac{36.68}{18.60}=1.9=2$, dopyric.

Rang, $\frac{CaO''+MgO+FeO}{Na_2O''}=\frac{613}{0}=1$, permirlic.

Section, $\frac{MgO+Feo}{CaO''}=\frac{426}{167}=2.5=2$, domiric.

Subrang, $\frac{MgO}{FeO}=\frac{368}{78}=4.9=2$, domagnesic.

Grad, $\frac{\text{E}}{\text{F}}=\frac{28.61}{7.79}=3.8=5$, prelenic.

Subgrad, $\frac{K_2O'+Na_2O'}{CaO'}=\frac{75}{19}=3.8=1$, prealkalic.

Reckoning in the BaO and SrO, the rock just crosses the line and becomes a dofemane. These other divisions have not been named, and no name is offered for them here, since a type standing more nearly in the center of each should be chosen. It is then salfemane-dofemane, bohemare-hungarare, etc., and the double name should be carried down. Since, however, the leucite is the most interesting component, and in the salfemanes the name albanase has appropriately been given to the domalkalic rang of the dolenic order to recall the fact that in the potassic subrangs leucite will be developed and the well-known Italian rocks will fall here, the name missourate may be used for the perpolic grad and missourote for the permirlic subgrad, to perpetuate the idea of a leucite-augite-olivine rock that is already connoted with this root.

Intermediate rock types.—The fact that this rock stands exactly on the line between the two classes shows that such transitional forms must occur in any system of classification which takes account of the relative quantities of minerals. They will be more numerous the more the rocks are studied and investigated. This is inherent in the very nature of rocks in which transitions occur in all directions, and is commonly looked upon by many petrographers as a difficulty, and a system of classification is regarded with favor if it professes to do away with such difficulties. There is a disposition on the part of many to regard such rocks as not typical, to say they are less abundant or not so important as those which fall in the middle of a unit, or to regard them as varieties or facies, or anything, in fact, which will minimize their importance and make the difficulty of classifying them less. The real difficulty lies not in the rocks, but in the petrographers. These difficulties will occur as long as petrographers endeavor to classify rocks into units which shall correspond to species in other domains of natural science and to force varied types to agree with such units. The main difficulties of each classification will disappear if it is recognized that there is no natural classification of rocks, and that the subject-matter spreads itself in a broad uninterrupted field, which is arbitrarily divided into units for convenience in description and nomenclature. Rocks which lie on the border will then be assigned to their proper place, their importance will be felt to be just as great as those away from dividing lines, and their systematic position will receive due consideration.

PETROGRAPHY OF THE DIKES AND SHEETS.

INTRODUCTION.

As the intrusive sheets of the Highwoods are geologically inconspicuous when compared with the dikes, and they have no petrographic characters which distinguish them from the dikes in such a degree that they deserve separate mention, the dikes and sheets are treated together in this description of their petrography.

In the field these rocks divide themselves roughly into light and dark types; in the language of the new classification, into salic and femic types. The persalanes, dosalanes, and salfemanes are represented, but no types more femic than these occur. Thus they represent the rocks found in the stocks and laccoliths in granular types. On the other hand, they are not much more differentiated than those, and the differences are chiefly textural ones, due to different physical conditions in cooling and crystallizing. These facts, merely alluded to here, will be discussed in their bearings in the chapter dealing with the petrology of the Highwood region.

In tabulated form the following types of rocks are found in the dikes and sheets, the names in both the old and the new classification being given for convenience:

Pulaskose or sölvsbergite-porphyry.
Highwoodose or tinguaite of Highwood type.
Monzonose or gauteite (monzonitic bostonite).
Borolanose or syenite-porphyry.
Cascadose or minette of Highwood type.
Monchiquose or analcite-basalt (monchiquite).
Monchiquose or leucite-basalt (leucite-monchiquite).

TRACHIPHYRO-PULASKOSE (SODALITE-SÖLVSBERGITE-PORPHYRY).

Introductory.—A rock of tinguoid habit is found on the divide between Middle and South peaks. It occurs in a narrow dike, but a few feet wide, which is one of the series cut off by the large intrusion of the Middle Peak stock whose contact edge runs along the divide.

Megascopic characters.—In the center of the dike the rock is a medium gray with almost no tone of green. The phenocrysts of feldspar are not strongly contrasted in shape and hue with the groundmass, as in some of the other feldspathic dikes, but are more or less formless and resemble it in color; they are tabular and attain a breadth of 10 mm. Occasional tiny specks of a black, pitchy mineral are seen. Near the contact the rock becomes much denser, the groundmass is a clear dark green, and the contrast with the phenocrysts is pronounced.

Microscopic characters.—In thin section the rock displays the usual characters of a tinguoid porphyry—phenocrysts of orthoclase and ægirite, with interior cores of ægirite-augite, rather thickly scattered in a groundmass of ægirite needles and microlites of alkali-feldspar arranged in marked trachytic texture. An occasional ore grain of apatite completes the list of the usual minerals. In addition there is found dark umber-brown melanite-garnet in well-defined dodecahedrons. It occurs in rather sparsely distributed, pitchy-looking specks on the rock surface, which may be seen with the naked eye. Its total amount is small. Melanite is not an uncommon constituent in this group of rocks, being mentioned in a number of occurrences. It has been found also in tinguaite (judithose) from the neighboring Judith Mountains.[a]

Another not very common feature of tinguoid rocks is the presence of considerable sodalite. It is seen in rather well-crystallized dodecahedrons, but in the coarse-grained rock at the center of the dike it is altered to zeolites, apparently natrolite. In the dense border facies it is clear, unaltered, and isotropic. That it is sodalite and not some other isotropic mineral is indicated by absence of sulphates, ready gelatinization, and strong reaction for chlorine.

The trachytic groundmass has in spots a flamed patchy appearance, which indicates the formation of zeolites, an assumption rendered probable by the water shown in the analysis. It is possible that it formerly contained some nephelite as a cement, or that some is still present, but this can not now be proved. The smaller microlites of ægirite in it are usually decomposed to earthy material, retaining the same columnar form.

Chemical composition.—The chemical analysis of this type is shown in I of the following table. It will be seen on comparison that it is much like other tinguaites, but shows a great preponderance of potash over soda, like the other rocks of this part of Montana.

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[a] Weed and Pirsson, Geology of the Judith Mountains: Eighteenth Ann. Rept. U. S. Geol. Survey, pt. 3, 1898, p. 571.

Analyses of tinguoid rocks.

	I.	II.	III.	IV.	V.
SiO_2	57.18	57.63	58.90	55.65	0.953
Al_2O_3	18.54	17.53	17.70	20.06	.181
Fe_2O_3	3.65	3.46	3.94	3.45	.023
FeO	1.15	1.18	2.37	1.25	.016
MgO	.69	.22	.54	.78	.017
CaO	2.31	1.35	1.05	1.45	.041
Na_2O	4.48	5.80	7.37	8.99	.073
K_2O	8.58	9.16	5.59	6.07	.091
H_2O	2.10	3.22	1.90	1.51	
TiO_2	.30	.33	.40	Trace.	.004
MnO	Trace.	Trace.	.55		
BaO	.49	Not det.	?		
SrO	Trace.	Not det.	?		
P_2O_5	.05	Trace.	Trace.		
SO_3	.06				
Cl	.77	.08			.022
	100.35	99.86	100.33	99.21	
O=Cl	.17	.03			
Total	100.18	99.83			

I. Tinguoid trachiphyro-pulaskose, from dike on ridge between Middle and South peaks. H. W. Foote, analyst.

II. Judithose (tinguaite-porphyry), from dike on Cone Butte, Judith Mountains, Montana. L. V. Pirsson, analyst. Weed and Pirsson, Geol. Judith Mountains, Eighteenth Ann. Rept. U. S. Geol. Survey, pt. 3, p. 569.

III. Umptekose (sölvsbergite-tinguaite) dike, on railroad between Tjose and Åklungen. V. Schmelck, analyst. Brögger, Grorudit-Tinguait-Serie, 1894, p. 102.

IV. Laurdalose (tinguaite) dike at Asbjörnsröd, Hedrum, South Norway. V. Schmelck, analyst. Brögger, Ganggefolge des Laurdalits, 1898, p. 377.

V. Molecular proportions of I.

Classification in the new system.—From the analysis just given it is easy to calculate the norm and the position of the rock in the new system. Without giving all the details of this in tabulated form, the results are shown in I of the table on the next page. The combination of high SiO_2 and the considerable amount of chlorine produces free quartz and sodalite.

The amount of chlorine in any case appears excessive and thus produces this anomaly. It is a good example of how carefully the small amount of chlorine in such rocks must be determined if it is to be used as a factor in determining the amount of sodalite present, and the same is true of SO_3 and nosean. Since no quartz is present in the

Calculation of the norms of tinguoid rocks.

	I.	II.	III.	IV.
Or	50.60	50.60	54.49	54.62
Ab	15.20	25.15	14.15	18.80
An	7.78	6.67		
Ne			12.50	8.81
So	10.65	5.81	.99	1.18
Qz	4.86			
Di	2.81	3.67	3.42	5.33
Ac			8.78	7.51
Hy	.40			
Wo			.93	
Mt	2.78	2.78	.70	
Il	.61	.61	.61	
Ht	1.76	1.76		
Rest	2.59	2.59	3.22	3.45
Total	100.04	99.64	99.79	99.70

I. Norm of pulaskose calculated from analysis.
II. Norm of pulaskose calculated with corrected chlorine.
III. Norm of judithose of Cone Butte.
IV. Mode of judithose of Cone Butte.

rock, we may distribute this silica so that it will raise a corresponding amount of sodalite to albite and diminish the chlorine accordingly. This gives 0.42 per cent of chlorine and the norm becomes that shown in II of the above table. The classification then becomes—

$$\text{Class, } \frac{\text{Sal.}}{\text{Fem.}}=\frac{88.23}{8.82}=10, =\text{I, persalane.}$$

$$\text{Order, } \frac{\text{L}}{\text{F}}=\frac{5.81}{82.42}=0.05=\text{perfelic}=5\text{, canadare.}$$

$$\text{Rang. } \frac{Na_2O'+K_2O'}{CaO'}=\frac{164}{24}=6.8=\text{domalkalic}=2\text{, pulaskase.}$$

$$\text{Subrang, } \frac{K_2O'}{Na_2O'}=\frac{91}{73}=1.2=\text{sodipotassic}=3\text{, pulaskose.}$$

It may be remarked that No. I above would lead to the same result, since $\frac{Q}{F}$ or $\frac{L}{F} \lessgtr \frac{1}{7}$ whichever be selected.

Since the study of the rock shows it to be porphyry of trachytic texture with feldspar phenocrysts, it may be designated trachisalphyro-pulaskose with tinguoid habit, or, more shortly, trachiphyropulaskose. This is a very condensed expression for a rock consisting chiefly of alkali feldspars, with ferromagnesian minerals less than 12.5 per cent, a small amount of anorthite feldspar in which soda and potash are molecularly about equal, and a porphyritic texture, with feldspar phenocrysts and a trachytic groundmass.

In this connection it is of interest to compare this rock with one of similar tinguoid habit from Cone Butte, in the Judith Mountains, previously described by the author. Its analysis is given in the table of analyses on page 123. It will be seen that it is similar in chemical composition, but contains less lime and higher alkalies. As a result of this it does not contain any anorthite, but a considerable amount of ægirite, and the larger proportion of femic minerals carries it into the dosalic class. This is shown on calculating its norm, which is given in III of the preceding table. Its actual mineral composition, or *mode*, is given in IV of the preceding table, and this is so close to the norm that the rock has very nearly a *normative mode.* From the norm and the analysis we may classify it as follows:

Class, $\frac{\text{Sal.}}{\text{Fem.}}=\frac{82.13}{14.44}=5.6=\text{II}$, dosalane.

Order, $\frac{L}{F}=\frac{13.49}{68.64}=.18$=lendofelic=6, norgare.

Rang, $\frac{K_2O'+Na_2O'}{CaO'}=\frac{173}{0}$=peralkalic=1, laurdalase.

Subrang, $\frac{K_2O'}{Na_2O'}=\frac{98}{75}=1.3$=sodipotassic=3, judithose.

The rock occupies a definite position in the subrangs, and for this reason the name of the occurrence has been given to it.

Mineral composition or mode.—The actual mineral composition, or *mode*, of the dike rock under description can not be determined with any great accuracy either from the analysis or from a study of its section. Combining both of these means of observation, it is reckoned that the mineral composition of the rock is approximately as follows:

Mineral composition or mode of trachiphyro-pulaskose.

Iron ore	2.0
Ægirite-augite	10.0
Orthoclase	50.0
Albite	10.0
Anorthite	3.0
Sodalite	10.0
Kaolin	7.0
Rest	8.0
Total	100.0

In this the full amount of chlorine given by the analysis is used to indicate the amount of sodalite, but it is thought that this is somewhat too high, and the amount shown in the norm is believed to be more nearly correct. The proportion of minerals is not strikingly different from that shown in the norm, and the rock, exception being made of the products of alteration, has in all probability a *normative mode.*

Classification in prevailing systems.—It is clear from the descriptions and analysis that in the prevailing systems of classification the rock is closely related to the sölvsbergites, the amount of feldspathoid being relatively small for the true tinguaites. It thus lies between the sölvsbergites and the tinguaites, and differs from the normal type in that nephelite is wholly or almost wholly replaced by sodalite. It is, therefore, a novel type and might be called a sodalite-potash-sölvsbergite-porphyry. This would without doubt have a very attractive sound to timid souls who fear the introduction of new names.

TRACHIPHYRO-HIGHWOODOSE (HIGHWOOD TINGUAITE-PORPHYRY).

Introductory.—The rock of the large gray dike which forms a conspicuous wall on the east side of the upper valley of Highwood Creek, a mile or so below the divide at Highwood, is about 12 feet wide and has broken through the dark, chocolate-colored breccias. In mass it has a somewhat platy structure, and it breaks in a splintery manner under the hammer. The rock has been previously described very briefly by Lindgren,[a] under the designation trachyte, type (*b*), as feldspathic porphyritic with phenocrysts of augite, biotite, and sanidine in a groundmass of the same minerals with opacite and some glass. He mentions especially the augite, which he considers to be the same throughout all of the Highwood rocks.

Megascopic characters.—On a surface of fresh fracture the rock is a medium greenish gray. This color is produced by great quantities of small dull-white phenocrysts very thickly sprinkled in a green gray groundmass of felsitic character. In size these phenocrysts run from 1 to 2 mm. in diameter, and have a more or less pronounced square outline. In addition there are a few dark specks of a ferromagnesian mineral scattered here and there, and occasionally one of these shows the glittering cleavage of a biotite. Examination with the lens only magnifies these features; it does not bring out anything in addition.

Microscopic characters.—In thin section there are seen to be present the following minerals in a compact groundmass: Iron ore, apatite, pyroxene, biotite, and orthoclase. Iron ore is found only as rare, small grains. Apatite is seen in occasional short, stout crystals. Biotite is also rather infrequent and occurs in small, somewhat rounded tablets, which are strongly pleochroic and have dark leather-brown and pale-yellow tones.

The pyroxene ranges in size from stout columnar crystals, 2–3 mm. long, down to scarcely perceptible needles. Usually they are well crystallized and bounded by the planes (100), (110), (010), and (111), in many cases (100) being largely developed. In color they are a clear pale green, which increases in depth from center to outside. In the largest crystals the center is almost colorless, and, in general, the smaller they are the deeper is the green color they exhibit. In the latter

[a] Tenth Census U. S., vol. 15, p. 726, section c.

case, also, they possess a faint but distinct pleochroism. The angle of extinction of $c \wedge \mathfrak{c}$ is large, being 45° or over. The double refraction has an index of 0.040 proximate, which is above that of pure diopside. All these characters show that the pyroxene is a diopside enriched to some extent with the ægirite molecule; it stands between diopside and an ægirite-augite.

The feldspar phenocrysts are considerably altered to kaolin in the hand specimens gathered, only interior cores being still fresh and clear. Gooch's[a] determination of the alkalies in them shows them to be of orthoclase (K_2O 11.36, Na_2O 2.14 per cent). They occur in Carlsbad twins and in intergrown groups. They do not have good crystal outlines and with high powers show in the clear portions no signs of any micro-intergrowths with the albite molecule.

The groundmass is of the usual type found in rocks of tinguoid habit. It consists of an interlaced mass of orthoclase laths woven through with a fine felt of ægirite needles, dotted here and there with small ore grains. Biotite, which could be referred to the groundmass, was not seen, all the crystals noted being distinctly in the class of phenocrysts. This groundmass is somewhat altered, as shown by the turbid, clouded appearance given it by the kaolin granules, making its study with high power difficult. There is also more or less of an isotropic substance present. The character of the rock and its geologic occurrence practically preclude its being a glass; moreover, the rock on treatment with dilute acid gelatinizes readily, and this again is impossible for an alkali-alumina glass. The solution yields the merest trace of chlorine, which excludes sodalite, and its ready gelatinization shows that the rock can not be wholly, at any rate, made up of leucite. All this points toward analcite, and the abundant water shown in the analysis renders this still more probable. Analcite is known to occur in the base of rocks of the tinguoid group, and recently Washington[b] has described one from the vicinity of Salem, Mass., which consists chiefly of this mineral in the groundmass and which he is inclined to view as being primary in origin. Coleman[c] also has described a tinguaite-like rock, under the name "heronite," whose base consists mostly of analcite which is regarded as primary. In the present case the amount of analcite is small compared with the other minerals, and there is nothing to show whether it was original or not. The rock is not perfectly fresh; but, on the other hand, that it is somewhat altered is no proof that the analcite is secondary, since it is known that in all probability it may occur as a primary component. With the means at command at the present time there is no way of telling in this instance whether it is primary or not.

Chemical composition.—The chemical analysis of this type is shown in column I of the table on the next page.

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[a] Tenth Census U. S., vol. 15, p. 726, sec. c.
[b] Am. Jour. Sci., 4th series, vol. 6, 1898, p. 182.
[c] Jour. Geol., vol. 7, 1899, p. 431.

Analyses of highwoodose and related tinguoid rocks.

	I.	II.	III	IV.	V.	VI.	VII.	VIII.	IX.	X.
SiO_2	58.04	57.18	57.46	57.63	58.70	58.90	62.70	55.65	0.967	0.953
Al_2O_3	17.25	18.54	15.40	17.53	19.26	17.70	16.40	20.06	.167	.180
Fe_2O_3	2.49	3.65	4.87	3.46	3.37	3.94	3.34	3.45	.015	.023
FeO	1.24	1.15	.87	1.18	.58	2.37	2.35	1.25	.017	.016
MgO	1.79	.69	1.37	.22	.76	.54	.79	.78	.045	.017
CaO	3.50	2.31	2.59	1.35	1.41	1.05	.95	1.45	.062	.041
Na_2O	3.37	4.48	5.48	5.80	8.55	7.37	7.13	8.99	.054	.072
K_2O	10.06	8.58	9.44	9.16	4.53	5.59	5.25	6.07	.107	.090
H_2O+	1.95	2.10	.82	3.22	2.57	1.90	.70	1.51	.107	.116
H_2O-			.09		.07					
CO_2	-------	-------	.13	-------	-------	-------	-------	-------	-------	-----
TiO_2	.30	.30	.60	.33	Tr.	.40	.92	Tr.	-------	-----
P_2O_5	.22	.05	.21	Tr.	.10	Tr.	-------	-------	-------	-----
SO_3	Tr.	.06	.13	-------	-------	-------	-------	-------	-------	-----
Cl	Tr.	.77	.20	.08	(?)	-------	-------	-------	-------	-----
F	-------	-------	Tr.	-------	-------	-------	-------	-------	-------	-----
MnO	Tr.	Tr.	Tr.	Tr.	.10	.55	-------	-------	-------	-----
BaO	([a])	.49	.60	([a])	-------	-------	-------	-------	-------	-----
SrO	([a])	Tr.	.16	([a])	-------	-------	-------	-------	-------	-----
Li_2O	Tr.	Tr.	Tr.	Tr.	-------	-------	-------	-------	-------	-----
	100.21	100.35	100.42	99.86	100.00	100.33	100.53	99.21	-------	-----
O=Cl	-------	.17	.05	.03	-------	-------	-------	-------	-------	-----
Total	-------	100.18	100.37	99.83	-------	-------	-------	-------	-------	-----

[a] Not determined.

I. Highwoodose (tinguaite-porphyry) from dike near head of Highwood Creek (No. 724). E. B. Hurlburt, analyst.

II. Pulaskose (tinguaite-porphyry) from dike cutting rim rock of Middle Peak stock, ridge between Middle and South peaks (No. 746). H. W. Foote, analyst.

III. Judithose (Tinguaite-porphyry) from dike at head of Bear Creek, Bearpaw Mountains, Montana. H. N. Stokes, analyst. Weed and Pirsson, Bearpaw Mountains of Montana, Am. Jour. Sci., 4th series, vol. 2, 1896, p. 192.

IV. Judithose (tinguaite-porphyry) from dike at Cone Butte, Judith Mountains, Montana. L. V. Pirsson, analyst. Weed and Pirsson, Geology of Judith Mountains, Eighteenth Ann. Rept. U. S. Geol. Survey, pt. 3, 1898, p. 569.

V. Miaskose (sölvsbergite) from intrusive sheet north of Shields River, Crazy Mountains, Montana. W. H. Melville, analyst. Wolff and Tarr, Acmite-trachyte from the Crazy Mountains, Bull. Mus. Comp. Zool., Cambridge, Mass., vol. 16, No. 12, 1893, p. 232.

VI. Umptekose (sölvsbergite-tinguaite) from dike on railroad between Tjose and Aklungen, 175 kilometers from Christania, Norway. V. Schmelck, analyst. Brögger, Grorudit-Tinguait-Serie, 1894, p. 102.

VII. Umptekose (hornblende-sölvsbergite) from Lougenthal, South Norway. L. Schmelck, analyst. Brögger, loc. cit., p. 80.

VIII. Laurdalose (tinguaite) dike at Asbjörnsröd, Hedrum, South Norway. V. Schmelck, analyst. Brögger, Ganggefolge des Laurdalits, 1898, p. 377.

IX. Molecular proportions of I.

X. Molecular proportions of II.

The notable features as compared with most rocks of pronounced tinguoid habit are the extraordinarily high potash in contrast with the soda and the high lime and magnesia. It is approached in this latter respect by the tinguaite from the Bearpaw Mountains. It will be seen by glancing at the column of molecular ratios (IX) that the lime is just sufficient to turn all the ferrous iron and magnesia into pyroxene. The considerable amount of water is to be attributed in part to the analcite and in part also to the kaolin. In this analysis as originally published[a] the amount of chlorine, 0.38 per cent, is undoubtedly too high. This would indicate somewhat less than 5 per cent of sodalite, or an amount somewhat smaller than that of chlor-apatite. Several very carefully conducted tests have failed to show more than a mere trace, which is undoubtedly from the small amount of apatite present.

Mineral composition or mode.—The mineral composition can not be accurately computed from the analysis on account of several uncertainties and because each oxide is or may be present in two or more components. The analysis affords, however, a certain amount of data, and from it and a study of the section it can be rather closely reckoned that the rock consists of 20 per cent augite, including 2 or 3 per cent of iron ore, apatite, etc., and 80 per cent feldspar and feldspathoids. Of the augite, about one-third to one-quarter is ægirite and there is about 10 to 15 per cent of analcite.

Classification in prevailing systems.—When one compares the analysis of this rock with that of typical tinguaites and sölvsbergites, it is seen to differ from them, as before mentioned, in potash, magnesia, and lime; and this is expressed in the minerals, since we have diopside and ægirite-augite instead of ægirite, orthoclase instead of soda orthoclase or albite, and analcite in place of nephelite. It is to be noted also that in silica and alumina it stands between a typical tinguaite and sölvsbergite, as may be seen by reference to analyses VII and VIII. The iron is lower than in most rocks of this group. The rather small amount of feldspathoid present evidently places the rock between the sölvsbergites and the tinguaites. All these facts show that, while by its structure and general composition it belongs in this group, it is evidently a distinct variety and may be called the *Highwood* type of tinguaite.

Classification in the new system.—In the new system of classification the rock occupies a definite position by itself among the subrangs, thus filling a position otherwise vacant, and for this reason the name of highwoodose has been given it, by which the dopotassic subrang of the peralkalic rang of the perfelic order of dosalane has been designated. This is shown in the following table of calculation of the norm.

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[a] Bull. U. S. Geol. Survey No. 148, p. 152, Analysis B.

Calculation of the norm of highwoodose.

	Analysis.	Molecular ratio.	Or.	Ab.	Ne.	An.	So.	Di.	Wo.	Mt.	Il.	Ap.	Ht.
SiO_2	58.04	0.967	642	168	12	22	30	90	3				
Al_2O_3	17.25	.167	107	28	6	11	15						
Fe_2O_3	2.49	.015								13			2
FeO	1.24	.017								13	4		
MgO	1.79	.045						45					
CaO	3.50	.062				11		45	3			3	
Na_2O	3.37	.054		28	6		20						
K_2O	10.06	.107	107										
TiO_2	.30	.004									4		
P_2O_5	.22	.001										1	
Cl_2	.38	.005					5						
Rest	1.95												
Total	100.59		107	28	6	11	5	45	3	13	4	1	2

Or	59.49	83.77
Ab	14.67	
An	3.06	
Ne	1.70	
So	4.85	
Di	9.72	14.36
Wo	.35	
Mt	3.02	
Il	.61	
Ht	.32	
Ap	.34	
Rest	1.95	
Total	100.08	

Class, $\frac{\text{Sal.}}{\text{Fem.}}=\frac{83.77}{14.36}=5.8$=dosalic=dosalane.

Order, $\frac{L}{F}=\frac{6.55}{77.22}=0.08$=perfelic=germanare.

Rang, $\frac{K_2O'+Na_2O'}{CaO'}=\frac{161}{11}=14.6$=peralkalic=umptekase.

Subrang, $\frac{K_2O'}{Na_2O'}=\frac{107}{54}=1.99$=dopotassic=highwoodose.

If we consider that the rock has evident phenocrysts of feldspar and a microtrachytic groundmass, it may be characterized as trachi-salphyro-highwoodose with tinguoid habit. The accordance between the norm and the mode is not complete, since analcite is developed at the expense of albite, and the ægirite of the mode shows itself in iron compounds in the norm; but on the whole these constitute a modal variety rather than a real abnormative mode.

ROCKS OF TINGUOID HABIT (GRORUDITE-TINGUAITE SERIES).

This group of rocks was first given a distinct and coherent form by Brögger[a] in a monograph which has become one of the classics of petrographic literature.

The series as described by him is a group of feldspathic rocks of dense to porphyritic character occurring in narrow dikes and sheets and composed chiefly of alkali feldspars and ægirite. According to the amount of silica present there will be free quartz (grorudite),

[a] Grorudit-Tinguait-Serie, 1894.

little or no quartz (sölvsbergite), or rocks containing nephelite (tinguaite) as a result of the deficiency of silica producing this molecule instead of albite. Rosenbusch[a] calls the series "rocks of tinguaitic habit" and refers to their green color and compact grain, which are indeed useful characters for megascopic determination.

Rocks of this series have been abundantly found in central Montana in the detached outlying mountain groups, and have been described by Mr. Weed and the author from the Bearpaw, Judith, and Little Rocky mountains, and by Wolff[b] from the Crazy Mountains, under the name of acmite-trachyte. In these places they occur as narrow dikes and sheets, more rarely as marginal facies of large laccolithic masses of syenitic rocks (Little Rocky and Judith Mountains).

As appears to be generally the case in these occurrences, the rocks are satellites, dependent on rock complexes of alkalic habit and character.

Thus in central Montana they are potash tinguaites, etc., evincing therefore the regional characteristic of this well-defined petrographic province—alkalic magmas with very high potash.

In the Highwood Mountains two occurrences of rocks having this habit have just been described, both in dikes, and it is of interest to note that while the Highwood group clearly belongs to the general central Montana province, yet the rocks composing it show throughout certain local peculiarities which determine them as belonging to one clan, and the tinguoid members have certain characteristics which stamp them as forming a subgroup of the series—the Highwood group—since they wear, so to speak, the Highwood tartan.

The new system of classification is traversed in various directions by serial rock groups, according as one or more elements vary and there is a greater or lesser amount of a given mineral or minerals in the rock. The same is, of course, true in all systems of classification. Thus in the new system the rocks of tinguoid habit will be found chiefly in the persalanes and dosalanes, and in the quardofelic, perfelic, lendofelic, and lenfelic orders in each class. In the rangs they occur in the peralkalic and domalkalic, and in subrangs chiefly in the dopotassic, sodipotassic, and dosodic. This would give in theory about 48 subrangs in which this habit might be developed. However, on inspection of well-known types occurring in these subrangs, it becomes evident that the habit is rare or little known in the domalkalic dosalanes, and the number mentioned above will be reduced to about 25 or 30. Moreover, the great mass of them will be found clustering in the subrangs rich in soda, in the alkalic rangs in quardofelic, perfelic, and lendofelic orders.

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[a] Elemente der Gesteinslehre, 1898, p. 211.

[b] Bull. Mus. Comp. Zool., Cambridge, Mass., vol. 16, No. 12, 1893, p. 232.

TRACHIPHYRO-MONZONOSE (GAUTEITE VARIETY OF BOSTONITE).

Occurrence.—In a small number of localities occur dikes and sheets of fine-grained, light-colored feldspathic rocks of more or less pronounced trachytic character. They are usually badly altered and weathered, so much so that in some instances they are merely crumbly masses of soil whose form, position, and more resistant contact zones on the sides alone enable them to be distinguished as dikes. On digging into such masses pieces of less altered rock may be found which enable one to recognize the type. In a very few instances they are well preserved and afford fresh material for study, as in the basin at the head of Aspen Creek, where two dikes on spurs on the north side of the main creek, west of the breccia hills, cut Cretaceous sediments. They are a mile or so apart, and, like the Highwood minette (shonkinose) dikes, they extend in the direction of the Shonkin stock. The eastern one is the larger, and is about 15 feet wide.

Megascopic characters.—In the hand specimen the rock is a pale brown, rather fine grained, and compact, but it has a markedly rough trachytic feel and appearance. This surface is rather thickly sprinkled with hornblende prisms, which are black and glittering on a cleavage face. The prisms are 10–20 mm. in length and 1–2 mm. broad. In some cases they are altered and brown or rusty. With the lens one sees also small, clear apatites; they are not common, but a considerable number may be found. The crystals are of unusual size for a rock of this character.

Microscopic characters.—Under the microscope the hornblendes are found to be of an olive-green and yellow pleochroic variety, allied to arfvedsonite and similar to the green hornblendes described in the border type of the rock of the Middle Peak stock (borolanose) and the green variety of the syenite of Square Butte (pulakose). The large apatites are well crystallized, with prisms and the common pyramid and base. They are colorless and without notable inclusions. A considerable amount of iron ore in small scattered grains is also present.

The groundmass in which these minerals lie is composed of lath-shaped feldspars, which at times tend to assume a somewhat tabular form. Careful study with high powers shows that they are sometimes untwinned, sometimes singly twinned according to the Carlsbad law, and sometimes are albite twins. Whether twinned or not, all sections whose form, edges, etc., show that they are cut in the zone perpendicular to 0.010 extinguish parallel with the nicol, and these facts in connection with the analysis prove that both alkalic and plagioclase feldspars are present and that the latter is an oligoclase. Undoubtedly the orthoclase contains considerable soda.

The chlorine and sulphur trioxide shown in the analysis would seem to indicate that considerable sodalite and nosean may be present. They are, however, not seen in the sections. A minute quantity of colorless isotropic substance is found in spots between the feldspars; this may be sodalite, but it may also be analcite, as indicated by the water. A little interstitial nephelite might also be present and escape detection. It is rather inferred that the chlorine and sulphur shown are somewhat too high, and that the chlorine comes for the greater part from the apatite, while a little pyrite might easily furnish the sulphur. It should be remembered that very small errors in the estimation of chlorine and sulphur within the limits of good analytical work will cause large variations in the amounts of sodalite and nosean estimated from them.[a]

This groundmass is somewhat stained by yellowish ferruginous material, which under the microscope is seen only in spots. There may be some zeolitization, as indicated by the water shown in the analysis.

Mineral composition or mode.—As nearly as this can be approximated, the rock contains about 5 per cent of iron ore, about 1.5 per cent of apatite, about 10 per cent of hornblende, and the rest is made up of about equal proportions of oligoclase and orthoclase feldspars.

Chemical composition.—An analysis of the large Aspen Creek dike, the eastern one of the two shown on the map, has been made by Doctor Foote, with the results shown in I of the table on the next page.

The moderate silica, high alumina, and alkalies show that this is essentially a trachytic rock, but the amount of lime, iron, and magnesia is too high for a typical rock of the class. The chlorine and sulphur have already been commented upon.

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[a] This has accordingly been taken into account in the calculation of the norm.

Analyses of monzonose (gauteite) and related rocks.

	I.	II.	III.	IV.	V.	VI.	VII.
SiO_2	55.23	54.15	55.52	57.29	58.18	56.75	0.920
Al_2O_3	18.31	18.25	20.05	18.45	18.46	18.37	.179
Fe_2O_3	4.90	3.62	2.52	4.38	2.31	2.22	.031
FeO	2.06	2.09	2.40	1.20	3.79	3.04	.029
MgO	1.85	2.56	2.10	2.08	1.99	2.02	.046
CaO	3.62	4.89	3.15	3.57	3.11	4.68	.064
Na_2O	4.02	4.43	3.44	4.43	3.70	4.85	.065
K_2O	6.43	6.56	7.49	5.43	6.58	5.92	.068
H_2O+	1.84	3.69	1.42	2.01	.64	.18	------
H_2O-	--------	--------	--------	.17	--------	--------	------
TiO_2	.42	Trace.	.70	.72	.68	1.24	.005
P_2O_5	.58	.41	.51	.46	.41	--------	.004
SO_3	.23	--------	--------	--------	--------	--------	------
Cl	.32	--------	Trace.	--------	--------	--------	------
NiO	--------	--------	--------	.12	--------	--------	------
MnO	Trace.	--------	--------	Trace.	--------	Trace.	------
BaO	.46	--------	--------	(?)	.29	--------	------
SrO	Trace.	--------	--------	(?)	(?)	--------	------
	100.27	--------	--------	--------	--------	--------	------
Cl=O	.08	--------	--------	--------	--------	--------	------
Total	100.19	100.65	99.30	100.31	100.14	99.38	------

I. Monzonose (gauteite) from Aspen Creek, Highwood Mountains. H. W. Foote, analyst.

II. Monzonose (gauteite) from Mühlörzen, Blatt Bensen, Bohemia. R. Pfohl, analyst.

III. Monzonose (gauteite) from Gentungan, Maros Peak, Borneo. Doctor Hinden, analyst.

IV. Monzonose (quartz-banakite) from Stinkingwater River, Yellowstone Park. W. H. Melville, analyst. Iddings, Jour. Geol., vol. 3, 1895, p. 947.

V. Monzonose (odinite) from Tito, Coquimbo, Chile. A. Lindner, analyst. F. v. Wolff, Zeit. Deutsch. Geol. Gesell., vol. 51, 1899, p. 531.

VI. Monzonose (ciminite) from L'Arso, Ischia, Italy. H. S. Washington, analyst. Am. Jour. Sci., 4th ser., vol. 8, 1899, p. 290.

VII. Molecular ratios of I.

Classification in prevailing systems.—A rock of this character, containing so much plagioclase and orthoclase, and of porphyritic texture, would lie between the andesites and trachytes, and would be classed as a trachyandesite. An analysis of a rock of this character is shown in VI. Under the heading of trachyandesitic dike rocks, following the system of Rosenbusch, a few years ago Hibsch[a] described bostonoid types from the region covered by the Bensen sheet of the Bohemian Mittelgebirge survey, which differed from true bostonites in containing considerable plagioclase. He expressly notes that on account of the nearly equal mixture of orthoclase and plagioclase they should be viewed as belonging to the monzonite family of Brögger, under which they represent the bostonites of the syenitic family. Having thus a distinct place of their own, he proposed for them the name gauteite, from the hamlet of Gaute, near which a group of these dikes occur. In mineral development they are similar to the type just described, with hornblendes and the trachytic groundmass, but have in addition some augite, biotite, and numerous plagioclase phenocrysts. Having thus a more pronounced porphyritic habit, they are less like typical bostonites than the Aspen Creek rocks. These themselves vary from a typical bostonoid habit in the fact that they carry a considerable number of phenocrysts of hornblende, the original types of bostonites consisting of a trachytic groundmass alone. Chemically the close correspondence between the gauteite of Aspen Creek and the original type of Hibsch is seen by comparing the analyses given in the table.

A somewhat similar rock from the Maros Peak complex in Celebes is also described as a gauteite by Schmidt.[b] Chemically it is closely related, as may be seen by comparing its analysis. In mineral development the groundmass is purely orthoclase with some sodalite, in which lie phenocrysts of labradorite and biotite. It has been found only as an erratic, and its dike nature is surmised. At present, therefore, it can only be provisionally placed with the gauteites.

Classification in the new system.—In this the type of the rock and the relations of orthoclase and plagioclase are shown by its falling into monzonase, where it properly belongs. This is seen in the following table.

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[a] Erläut. zur geol. Karte des Böhm Mittelgeb., Blatt Bensen, Tschermaks Min. Mitt., vol. 17, p. 84

[b] Sarasin's Celebes, vol. 4, 1901, appendix, p. 19.

Calculation of the norm of monzonose.

	Analysis.	Molecular ratio.	Or.	Ab.	Ne.	An.	Di.	Hy.	Mt.	Il.	Ht.	Ap.
SiO_2	55.23	0.920	408	360	10	92	10	41				
Al_2O_3	18.31	.179	68	60	5	46						
Fe_2O_3	4.90	.031							24		7	
FeO	2.06	.029							24	5		
MgO	1.85	.046					5	41				
CaO	3.62	.064				46	5					13
Na_2O	4.02	.065		60	5							
K_2O	6.43	.068	68									
TiO_2	.42	.005								5		
P_2O_5	.58	.004										4
Cl_2	.07	.001										1
Rest	2.53											
Total	100.02		68	60	5	46	5	41	24	5	7	4

Or	37.81	83.46
Ab	31.44	
An	12.79	
Ne	1.42	
Di	1.08	13.97
Hy	4.10	
Mt	5.57	
Il	.76	
Ht	1.12	
Ap	1.34	
Rest	2.53	
Total	99.96	

Class, $\frac{\text{Sal.}}{\text{Fem.}}=\frac{83.46}{13.97}=5.9=$II, dosalane.

Order, $\frac{L}{F}=\frac{1.42}{82.04}=.017=$perfelic$=5$ germanare.

Rang, $\frac{Na_2O'+K_2O'}{CaO'}=\frac{133}{46}=2.9=$domalkalic$=2$, monzonase.

Subrang, $\frac{K_2O'}{Na_2O'}=\frac{68}{65}=1.0=$sodipotassic$=3$, monzonose.

The texture is clearly microscopic trachytic; it is porphyritic with hornblende phenocrysts alone; it is thus alferphyric and should be termed trachiphyro-hornblende-monzonose.

TRACHIPHYRO-BOROLANOSE (SYENITE-PORPHYRY).

Occurrence.—In a number of places in the Highwoods occurs a dike rock which, by reason of its chemical, mineralogical, and textural peculiarities, has a definite place of its own, and in its appearance affords a particular and easily recognizable type. One dike (832) cuts leucite-basalt and breccia near the Shonkin stock at the head of Shonkin Creek; another (783), whose broken down exposure consists of large plate-like slabs, is found in basaltic flows and breccias in the spur running north from the main ridge which terminates in Twin Peaks, just below the central summit on the main ridge; another (861) cuts a black pinnacle of basaltic breccias at the head of a west branch of upper Shonkin Creek, near the Arnoux stock, on the divide to Highwood Creek. One example (703) cuts a spur running up toward the mountain ridge on the west side of Highwood Gap; another (682) forms the crest of a little hill in the open country south of South Peak. The dike is about 25 feet wide and weathered down. The rock is platy, has rather large phenocrysts of feldspar, and is considerably altered and brownish from weathering. Still another, on the west side of Highwood Gap (697), is much weathered and broken down and cuts a small intrusion of another rock and also the basaltic dikes. These dikes have a width of from 6 to 10 feet and cut the basaltic dikes and breccias. The last example (745) is one of the dikes on the summit ridge leading to South Peak. It is greatly weathered and kaolinized. The feldspar phenocrysts are small, but the microscope shows that the rock belongs in this type.

Megascopic characters.—In the hand specimens these rocks are of a general pearl-gray color. They are distinct porphyries. The phenocrysts consist of numerous tabular alkalic feldspars which attain dimensions of 12 by 2 mm. and are not of very good crystal form, small black glittering prisms of augite, and hexagonal tables of biotite. They are thus to be classed as alfersalphyric in character. These components are in general without arrangement in the gray groundmass, which is evidently granular and made up of a lesser quantity of the tiny femic grains among the salic ones. In two instances, however, the thin tabular feldspar phenocrysts are arranged in a markedly oriented manner parallel to the walls of the dike and show a pronounced flow structure.

None of these occurrences affords perfectly fresh material. The newly fractured rock face is dead and lusterless; the feldspar cleavages lack sparkle, and the larger phenocrysts have a white porcelain-like look which shows that they are more or less altered. These observations do not apply to the alferric minerals, which are generally well preserved. On weathered surfaces the rock exhibits a light-brown crust, and in the more altered occurrences it is brown throughout.

Microscopic characters.—In the thin sections the minerals seen are magnetite, apatite, diopside, biotite, and alkali feldspars. The iron ore and apatite present no especial peculiarities. The mica is a brown biotite of ordinary character. The diopside varies from very pale to a clear green; it rarely shows pleochroism, has a wide extinction angle, and is well crystallized in columnar forms; it is of the regular Highwood type described elsewhere. A few pieces of a pleochroic ægirite-augite were observed in some sections. The feldspars are of the usual character of orthoclase; they undoubtedly contain soda, as shown by the analysis. They are either untwinned, which is common among the phenocrysts, or singly twinned Carlsbads, which are very common in the lath-like development in the groundmass. The phenocrysts vary much in size, not only in the different occurrences, but also in the same section, and there are formal transitions from phenocryst to groundmass. The phenocrysts in all cases are abundant and thickly scattered. Very few feldspars that could be recognized as of plagioclase would be formed, and as these were in the more altered types the species could not be determined.

In the groundmass the small lath-like feldspars vary considerably in size in the different dikes, but they all have the same form and the trachytic texture, and in general are interwoven without arrangement; in some cases there was seen a tendency to form radial divergent groups, resulting in a fabric suggesting remotely the spherulitic.

The microscope shows that the ferromagnesian minerals are fresh and well preserved, while even in the best material the feldspars are considerably altered and brown with kaolin. This is especially true of those in the groundmass, and this brownish scattered kaolin dust prevents the study of the interspaces between the groundmass feldspars. It may be safely said, however, that there is no quartz, and this fact, combined with the low silica and the presence of some chlorine and sulphuric anhydride in the type analyzed, leads to the suspicion that the rocks when fresh probably contained in these interspaces small amounts of lenad minerals—nephelite, sodalite, and nosean. Some of the larger phenocrysts of feldspar contain colorless isotropic bays and areas of what is probably secondary analcite.

Chemical composition.—For the purpose of chemical examination the rock of the dike cutting the Shonkin stock was selected as the one affording the best material. The analysis, made under the writer's direction by Dr. W. M. Bradley, resulted as shown in the table on the next page.

The features of this analysis are the low silica combined with high lime and alkalies and the predominance of potash over soda. The amount of alteration mentioned is shown by the rather considerable amount of water. As a whole the analysis is typical for the general salic types of the Highwoods, and the analogy of this dike rock with the salic granular stock rocks is seen by comparing it with them. There is given for comparison the analyses of the stock of Middle Peak and of several similar rocks from other parts of the world. The close similarity to the granular rocks of the stocks and the geologic occurrence tend to show that these dikes are intrusions of the same general stage of differentiation in the magma basin below, for just as the salic portions of the stocks break up through the femic ones, so these salic dikes cut the femic dikes. The type above analyzed cuts the femic extrusives near the Shonkin stock.

Analyses of borolanose and related rocks.

	I.	II.	III.	IV.	V.	VI.
SiO_2	51.94	52.05	49.70	47.8	51.02	0.866
Al_2O_3	15.78	15.02	18.45	20.1	18.63	.155
Fe_2O_3	4.07	2.65	3.39	6.7	3.14	.026
FeO	3.17	5.52	4.32	.8	.84	.044
MgO	3.48	5.39	2.32	1.1	1.02	.087
CaO	6.04	8.14	7.91	5.4	7.89	.107
Na_2O	3.44	3.17	5.33	5.5	4.13	.055
K_2O	7.69	6.10	4.95	7.1	6.08	.082
H_2O	2.17	.35	1.34	2.4	1.10	------
TiO_2	.39	.47	1.33	.7	Tr.	.005
MnO	Tr.	Tr.	Tr.	.8	.59	------
BaO	.42	.42	------	.8	CO_2 4.53	------
SrO	.28	.28	------	------	Fl. Tr.	------
P_2O_5	.59	.21	.40	------	.16	.004
SO_3	.29	.02	------	.4	.29	.004
Cl	.08	.24	------	------	.09	.002
	99.83	100.03	------	------	------	------
Less O	.02	.06	------	------	.02	------
Total	99.81	99.97	99.44	99.3	99.64	------

I. Trachiphyro-borolanose (syenite-porphyry) from dike near Shonkin stock, Highwood Mountains. W. M. Bradley, analyst.

II. Grano-borolanose (basic syenite, syenomonzonite), main type of Middle Peak stock, Highwood Mountains. E. B. Hurlburt, analyst.

III. Borolanose (covite) from schoolhouse, Magnet Cove, Ark. H. S. Washington, analyst. Jour. Geol., vol. 9, 1901, p. 612.

IV. Borolanose (borolanite) from Lake Borolan, Sutherland, Scotland. J. H. Player, analyst. Horne and Teall, Trans. Royal Soc. Edinburgh, vol. 37, pt. 1, 1892, p. 178.

V. Borolanose (phonolite) from Gennersbohl, Hegau, southern Germany. G. F. Föhr, Inaug. Diss., Wurzburg, p. 24, 1883. (Including Cu 0.15 and trace Cr_2O_3.)

VI. Molecular proportions of No. I.

Mineral composition or mode.—The actual quantitative mineral composition or mode of this rock can not be definitely reckoned from the analysis, since the presence of the augite and biotite introduces too many unknown factors. It can not be accurately determined by the microscope because the condition of the feldspathic groundmass does not permit of accurate separation of its component parts. If, however, the groundmass is considered merely as so much feldspar, and no attempt is made to separate the individual microlites or to determine the amount of material in their interspaces, a fairly accurate computation of the other minerals as contrasted with the feldspars may be made by repeated measurements. The results are as follows:

Actual mineral composition of borolanose.

	Measured units.	Volume, per cent.		Specific gravity.				Weight, per cent.
Feldspar	1,841	71.1	×	2.6	=	184.86	=	64.6
Biotite	254	9.9	×	3.0	=	29.90	=	10.4
Diopside	302	11.7	×	3.3	=	38.61	=	13.5
Magnetite	124	4.7	×	5.2	=	24.44	=	8.5
Apatite	68	2.6	×	3.2	=	8.32	=	3.0
Total	2,589	100.0				286.13		100.0

In all 150 measurements were made, giving an average of 17 units on the scale for the grains, feldspars not subdivided into individual microlites. The last column gives the approximate percentage composition by weight.

Classification in prevailing systems.—In the prevailing systems of classification this rock has no very definite position. The alkalic feldspars and ferromagnesian minerals place it in a general way in the syenite family, of which it would be a very basic member. Its chemical composition allies it with the monzonites, from which it is excluded by the lack of plagioclase feldspar. In spite of the high lime, there is molecularly enough ferrous iron and magnesia to convert the lime into diopside and prevent the formation of plagioclase. On the other hand, the presence of a certain amount of the feldspathoid minerals, but not enough to carry it into the nephelite-syenite family, in conjunction with the large amount of ferromagnesian minerals, produces tendencies toward the essexites. On the whole, considering both the minerals and the chemical composition, the name syenite-porphyry would perhaps best suit it, though it is a divergent type of this family.

Classification in the new system.—In the new classification the rock has a definite position, determined by its standard mineral composition calculated from its analysis, as may be seen by the annexed table:

Calculation of the norm of borolanose.

	Analysis.	Molecular ratio.	Or.	Ab.	An.	Ne.	So.	No.	Di.	Ol.	Mt.	Il.	Ap.
SiO_2	51.94	0.866	492	108	46	46	6	12	142	15			
Al_2O_3	15.78	.155	82	18	23	23	3	6					
Fe_2O_3	4.07	.026									26		
FeO	3.17	.044							9	4	26	5	
MgO	3.48	.087							62	25			
CaO	6.04	.107			23				71				13
Na_2O	3.44	.055		18		23	4	10					
K_2O	7.69	.082	82										
TiO_2	.39	.005										5	
P_2O_5	.59	.004											4
Cl_2	.08	.002					1						1
SO_3	.29	.004						4					
Rest	2.87												
Total	99.83		82	18	23	23	1	2	71	15	26	5	4

Or	45.59	
Ab	9.43	
An	6.39	71.18
Ne	6.53	
So	.97	
No	2.27	
Di	15.63	
Ol	2.16	
Mt	6.03	25.92
Il	.76	
Ap	1.34	
Rest	2.87	
Total	99.97	

Class, $\frac{\text{Sal}}{\text{Fem}}=\frac{71.18}{25.92}=2.3=$II, dosalane.

Order, $\frac{\text{L}}{\text{F}}=\frac{9.77}{61.41}=.157=$lendofelic$=6$, norgare.

Rang, $\frac{Na_2O'+K_2O'}{CaO'}=\frac{137}{23}=5.9=$domalkalic$=2$, essexase.

Subrang, $\frac{K_2O'}{Na_2O'}=\frac{82}{55}=1.5=$sodipotassic$=3$, borolanose.

The calculation shows that the rock is very near the upper limit in its rang; it is thus close to the peralkalic rang laurdalase, in which Na_2O+K_2O : CaO as 7:1 or greater than that. It is, therefore, very near judithose, the sodipotassic subrang of laurdalase, and Washington, in his tables of calculated analyses (p. 295), places it in that subrang, the omission of the small amount of sodalite giving a larger amount of nephelite, and this in turn less anorthite, thus causing it to just fall over the line in judithose.

On account of the condition of the groundmass, which prevents the determination of the actual amount of lenad (feldspathoid) minerals present, a good comparison can not be made between the norm and the mode of this rock. As shown elsewhere in this paper, in the Highwood rocks olivine and lenad molecules have frequently united to form biotite; the presence of about 10 per cent would cause the rock to be a modal variety of a typical borolanose.

From all that has been said it is clear that in the new system the rock should be termed biotitic trachiphyro-borolanose, which is a very concise expression for a rock in which the feldspathic minerals are present in greater amount than the ferromagnesian ones; in which the alkali feldspars dominate over the plagioclase ones, and both of these over feldspathoids and a small amount of biotite which accompanies normative diopside; in which potash and soda are approximately equal molecularly, and in which the texture is porphyritic, with a trachytic groundmass.

PHYRO-BIOTITE-CASCADOSE (MINETTE OF HIGHWOOD TYPE).

Occurrence.—In the Highwood Mountains are many dike rocks which have a dark basaltic character, with numerous prominent biotite phenocrysts. They may well be characterized by the field name "mica traps" or "mica-basalts." The Highwood rocks do not, as a rule, yield perfectly fresh material in their outcrops. This characteristic is in no type so marked as in the one about to be described. Usually these dikes are greatly weathered and broken down, and often their position is marked merely by heaps of gravelly débris in which are thickly scattered the chloritized plates of biotite forming the large phenocrysts, enabling one to recognize this particular type and distinguish it from the other basaltic dike rocks.

There are so many of these dikes in this area that it would be useless to attempt to give a list and description of all of them. They were found in every stage of preservation, from those just mentioned to a few which afford really good material and are well suited for study and description.

One of these (736) cuts basaltic flows and breccias on the crest of the divide between Lava and Arrow peaks and near the slope of the latter. It is about 6 feet wide and extends in the direction of Middle Peak. Another occurs at the eastern edge of the stock of granular rock on the crest of the Middle Peak–South Peak ridge, and is similar to the former in character. A third (678) is found as a sheet intruded into Cretaceous sandstones at the head of a little fork of Williams Creek in the open country south of the Highwood Mountains. The sheet is 10 to 12 feet in thickness and rests on the sandstone. The drainage has cut through both, forming a small, narrow gulch. The upper part of the sheet has weathered and is crumbly, the lower portion is dense, very tough, and well preserved. It has not altered the beds into which it is intruded. It is noticeable that both in the Middle Peak divide dike (744) and in this occurrence the large, flat micas are oriented in a flow structure, in the dike perpendicularly and parallel to its vertical walls and in the sheet horizontally and parallel to the bedding. In the plane of these micas the rock splits rather readily. The weathered surface of these rocks shows a brown crust. They have a very massive parting structure, breaking into large, heavy blocks, with a poorly developed spheroidal or "pillow" structure. Sometimes on the surface of the contraction planes zeolites are developed.

Megascopic characters.—On a freshly broken surface the rock is a very dark stone-gray, almost black, with a tendency to conchoidal splintering; the grain is very fine, but not absolutely aphanitic. In the Williams Creek sheet the grain is somewhat coarser and the color somewhat lighter. Thickly scattered in this groundmass are numerous phenocrysts of biotite, whose average cross section measures about 5 mm., but at times reaches 10 mm. They are black and glittering, with bronzy reflections. The prisms and pinacoid (010) are only moderately well developed as a rule, sometimes the clinopinacoid (010) is much longer in its development than the prisms (010). The crystals are rather thin tabular. These large biotites and the basaltic character of the rock produce a strong similarity in habit to the "alnöites."

In addition to these—the characteristic phenocrysts of the rock—there are greenish grains of olivine and occasional but much rarer phenocrysts of a black, well-crystallized augite in moderately stout prisms, which in some cases attain a length of 5 mm. These last two are somewhat variable in the different occurrences.

Microscopic characters.—Under the microscope the minerals seen are apatite, iron ore, diopside, biotite, olivine, feldspars, and feldspathic groundmass products. Apatite is moderately abundant in a few large irregular grains and many small prisms. Iron ore is also abundant in small grains dotting the groundmass.

The pyroxene is a colorless to pale-green diopside without any noticeable pleochroism, of a wide extinction angle, and generally rather long columnar in development. It is well crystallized, with sharp angles and clean faces. It does not contain many inclusions, but some of the very largest crystals are somewhat spongy with inclusions of a brown glass. The small prisms of the groundmass are similar to the larger phenocrysts; various transitions in size between the two occur.

The large biotite phenocrysts are a pale yellowish brown; their pleochroism is not intense. They do not show very good crystal form and are apt to be embayed and ragged on the edges. They also have a narrow mantle around the outer edge, of a much darker color and more intense pleochroism. In these characters they recall the micas of many "minettes," as, for example, those figured by the author[a]

[a]Petrography of the Little Belt Mountains: Twentieth Ann. Rept. U. S. Geol. Survey, pt. 3, 1900, pl. 76, p. 528.

in such rocks from upper Sheep Creek in the Little Belt Mountains of Montana. Small biotites in thin tablets with sharp outlines are abundant in the groundmass; they have the deep-brown color and intense pleochroism of the border zones of the large phenocrysts.

From what has been said it seems clear that the large micas are of intratelluric origin; that they came up in the magmas into the dike fissures and were oriented parallel to its walls; that during this time they were in part resorbed, but grew again during the final stage of crystallization, adding material of the same character as the smaller crystals forming in the groundmass.

The olivine is somewhat variable; it is most abundant in the Middle Peak divide dike, but is not common; it is less abundant in the Arrow Peak dike, and is almost wholly wanting in the Williams Creek sheet. The few scattered crystals are not large nor particularly well crystallized.

All of these ferromagnesian minerals, both femic and alferric, are fresh and unaltered, except that cracks in the olivine show small lines of serpentinization, and the largest augites in the Williams Creek sheet show some calcite.

The groundmass of these rocks is, relatively to the total amount of phenocrysts, in minor amount, and is somewhat variable in character. It consists chiefly of orthoclase, or, perhaps better, alkali feldspars, in lath-like forms. In the Williams Creek occurrence this is mixed, however, with a subordinate amount of andesine, and in the other two occurrences there is more or less cloudy, feebly polarizing material of indefinite character. As this base is somewhat altered and brown from kaolinization, the exact character of these substances can not be made out. In the Arrow Peak dike it was noticed, however, that some of these areas were outlined by iron-ore grains, bits of pyroxene, mica, etc., into circular forms, and that these were more or less isotropic; and in one of these, in spite of the somewhat kaolinized condition, a cross twinning, exactly like that of leucite, could be made out, especially by the aid of the sensitive tint. In other places plumose bundles of fibers resembling spherulites, and no doubt of zeolitic nature, are seen.

In short, the base, while chiefly alkali feldspar, is accompanied sometimes by small amounts of andesine, sometimes of leucite, sometimes of nephelite, or mixtures of these, somewhat zeolitized and kaolinized.

Chemical composition.—For the purpose of studying the chemical character of these rocks the Arrow Peak dike was selected as the freshest and best. In the next table is given the analysis of this rock, by Dr. H. W. Foote, as well as analyses of related rocks. From these it will be seen that these dikes are of the same general magma

Analyses of biotite-cascadose and related rocks.

	I.	II.	III.	IV.	V.	VI.
SiO_2	46.04	47.88	48.95	48.36	46.73	0.767
Al_2O_3	12.23	12.10	12.98	12.42	10.05	.120
Fe_2O_3	3.86	3.53	3.63	5.25	3.53	.024
FeO	4.60	4.80	4.68	2.48	8.20	.064
MgO	10.38	8.64	11.73	9.36	9.27	.259
CaO	8.97	9.35	7.66	8.65	13.22	.161
Na_2O	2.42	2.94	2.31	1.46	1.81	.039
K_2O	5.77	5.61	3.96	3.97	3.76	.062
H_2O	2.87	2.22	3.16	5.54	1.24	--------
TiO_2	.64	.77	.49	1.18	.78	.008
MnO	Trace.	.15	.13	.13	.28	--------
BaO	.48	.46	--------	.29	?	--------
SrO	.25	.13	--------	--------	?	--------
P_2O_5	1.14	1.11	.67	.84	1.51	--------
SO_3	Trace.	None.	--------	--------	--------	.008
Cl	.11	Trace.	--------	--------	.18	.004
	99.76	99.69	--------	--------	100.56	--------
O=Cl	.03	X .30	--------	--------	.04	--------
Total	99.73	99.99	100.35	99.93	100.52	--------

I. Phyro-biotite-cascadose (minette or mica-basalt) from dike near Arrow Peak. H. W. Foote, analyst.

II. Montanose (shonkinite) from Shonkin Sag laccolith. W. F. Hillebrand, analyst. (X=CO_2, 0.12; ZrO_2, 0.03; F, 0.05; S, 0.025; Cr_2O_3, 0.035; V_2O_3, 0.04=0.30.)

III. Lamarose (absarokite) from dike at head of Lamar River, Yellowstone Park. L. G. Eakins, analyst. (Iddings, Jour. Geol., vol. 3, pp. 938, 943, 947.)

IV. Absarakose (absarokite) from dike south of Clark Fork, Absaroka Range, Wyoming. L. G. Eakins, analyst. Loc. cit.

V. Shonkinose (shonkinite) from Square Butte. L. V. Pirsson, analyst. Bull. Geol. Soc. America, vol. 6, 1895, p. 414.

VI. Molecular proportions of I.

as the shonkinose (shonkinite) and montanose forming the granular massives of the region, and that their texture and, to a considerable extent, their actual mineral composition have been modified by their physical environment. They are not, therefore, of magmas very different from the stocks which they accompany, but in reality are lamprophyres or differentiated femic dikes, as may be seen by comparison with the salic ones (aplitic or leucocratic forms), thus agreeing with the differentiation seen in the laccoliths and stocks or the massives themselves.

Under the name "absarokite," Iddings,[a] in 1895, described a number of rocks which occur in dikes and flows and which are of basaltic habit, with abundant phenocrysts of olivine and augite in a groundmass consisting of alkali-alumina minerals, chiefly alkali feldspars, with small amounts of plagioclase or leucite or altered feldspathoids, and a second generation of the phenocrystic minerals, sometimes accompanied by biotite. By reference to the foregoing table it will be seen that there is a close general resemblance between absarokites and the cascadose or minette under description, but they differ in minerals and in habit, as the cascadose contains a large amount of biotite in large and abundant phenocrysts. In the new system of classification absarokite appears in a subrang of its own under the order gallare.

Mineral composition or mode.—The quantitative mineral composition differs somewhat from the calculated norm, and the rock can not be said to have a normative mode. This is due to the fact that the greater part of the olivine, some of the magnetite, and some of the feldspathic molecules have united to form biotite. The microscopic analysis of the rock by Rosiwal's method gives the following results:

Mode of phyro-biotite-cascadose.

	Measured units.	Volume, per cent.		Specific gravity.				Weight, per cent.
Feldspar	645	45.4	×	2.6	=	118.0	=	39.2
Biotite	226	15.8	×	3.0	=	47.4	=	15.8
Olivine	98	6.9	×	3.3	=	22.8	=	7.6
Diopside	379	26.7	×	3.3	=	88.1	=	29.3
Magnetite	54	4.0	×	5.2	=	20.8	=	6.9
Apatite	18	1.2	×	3.2	=	3.8	=	1.2
Total	1,420	100.0				300.9		100.0

In the feldspar item there is included not only the alkalic feldspars which make up the bulk of the feldspathic base, but the lenad (feldspathoid) minerals as well. Owing to the conditions of their

[a] Jour. Geol., vol. 3, 1895, p. 935.

admixture and the clouding by kaolinization it is impossible to measure them separately with any degree of certainty, though taken together they can be measured as a whole with ease and accuracy. The results given in the above table are of interest; they appear at first sight to differ considerably from the norm given later, but when examined it will be found that the only important divergence is in the presence of about 16 per cent of biotite which has been formed at the expense of some of the olivine and feldspathic minerals in the norm. If this is true, the weight of the feldspathic minerals plus the olivine in the norm should equal the feldspathic minerals plus the biotite plus the olivine of the mode. This results as follows:

$$\overset{\text{F.}}{48.76}+\overset{\text{Ol}}{13.00}=61.76=\overset{\text{F.}}{39.2}+\overset{\text{Bi}}{15.8}+\overset{\text{Ol}}{7.6}=62.6$$

The result is as close as could be expected. Bearing this fact in mind, it will be seen that on the whole the agreement between the calculation from the chemical analysis and the result of microscopic analysis is reasonably close. About 6 per cent of olivine and about 10 per cent of feldspathic molecules have been united to form about 16 per cent of biotite. In composition biotites vary considerably, as may be seen by reference to tables of analyses of them; the one from the "monchiquite" of Horberig, Oberbergen has about equal parts of olivine and lenad molecules. Splitting the biotite up in the proportions mentioned above, we have the adjoined comparison between the norm obtained from the analysis and from the corrected mode:

Comparison of norm with mode of cascadose.

	Norm.	Mode.
F	48.76	49.2
Ol	13.00	13.4
Di	25.04	29.3
M	6.79	6.9
Ap	2.69	1.2

Had the feldspathic base been fresh and clear, no doubt equally good results could have been obtained from it.

Classification in prevailing systems.—In the prevailing systems these rocks should probably be classed as minettes; they are lamprophyric dikes consisting chiefly of alkali feldspars, biotite, and augite, with abundant phenocrysts of biotite and none of the feldspars. The minettes are not a well-defined group chemically, as may be seen by reference to the table of analyses given by Zirkel,[a] but these types

[a] Lehrbuch der Petrographie, vol. 2, 1894, p. 349.

differ in a considerable degree from the common ones, and the lenad (feldspathoid) minerals found in the base accentuate this point. Their most marked feature is the large biotite phenocrysts, which give them a strong alnöid habit. They might be called the Highwood type of minettes.

Classification in the new system.—In the new classification these rocks belong in the sodipotassic subrang of kamerunase, as may be seen by the calculation of the analysis into its standard mineral composition, shown in the annexed table. The norm derived from this and the classification are given below.

Calculation of the norm of biotite-cascadose.

	Analysis.	Molecular ratio.	Or.	Lc.	Ne.	So.	An.	Di.	Ol.	Mt.	Il.	Ap.
SiO_2	46.04	0.767	258	76	62	12	42	228	88			
Al_2O_3	12.23	.120	43	19	31	6	21					
Fe_2O_3	3.86	.024								24		
FeO	4.60	.064						13	19	24	8	
MgO	10.38	.259						101	158			
CaO	8.97	.161					21	114				26
Na_2O	2.42	.039			31	8						
K_2O	5.77	.062	43	19								
TiO_2	.64	.008									8	
P_2O_5	1.14	.008										8
Cl_2	.11	.002				2						
Rest	3.60											
Total	99.76		43	19	31	2	21	114	88	24	8	8

Or	23.91	
An	5.84	
Lc	8.28	48.76
Ne	8.80	
So	1.93	
Di	25.04	
Ol	13.00	
Mt	5.57	47.42
Il	1.22	
Ap	2.69	
Rest	3.60	
Total	99.88	

Class, $\frac{\text{Sal.}}{\text{Fem.}}=\frac{48.76}{47.42}=1.0=$III, salfemane.

Order, $\frac{\text{L}}{\text{F}}=\frac{19.01}{29.75}=.64=$lenfelic$=7$, kamerunare.

Rang, $\frac{Na_2O+K_2O}{CaO'}=\frac{101}{21}=5=$domalkalic$=2$, kamerunase.

Subrang, $\frac{K_2O}{Na_2O}=\frac{62}{39}=1.6=$sodipotassic$=3$, cascadose.

In class it stands at the center point; in order it is not far from the line, and is therefore near portugare; in rang it is near the top, not very far from the peralkalic line, and thus close to subrang 3 in malignase. It differs from montanose in containing smaller amounts of silica and lime, but the main cause of difference in classification lies in the difference in the relative amount of alkalies and alumina available in felic (feldspathic) and lenic (feldspathoid) molecules, which produces nearly twice as much anorthite in this rock, sufficient to carry it into a domalkalic rang.

Texture and name.—From what has been said it is clear that these rocks are holocrystalline granular, with a finely granular to aphanitic base. In fabric they are porphyritic, and since the dominant phenocryst is biotite they are alferphyric.

In the new classification this subrang under the salfemanes was not named, and in Washington's[a] tables of analyses it was represented by this rock alone. It is therefore proposed to call the subrang cascadose, from Cascade County, Mont., where the type described occurs.

Since the mode is abnormative, and biotite, which is the critical mineral, is alferric and appears largely in phenocrysts, the rock may be designated an alferphyro biotite-cascadose, or more concisely phyrobiotite-cascadose. This is a very concise and definite expression to indicate a rock which is made up of about equal parts of salic and femic minerals, in which the feldspathic dominate over the lenad (feldspathoid) molecules and both together over the anorthite molecule; in which potash and soda are present in approximately the same quantity; in which both femic and salic mineral molecules have united to form a good deal of biotite, and which is megascopically porphyritic with phenocrysts of biotite. The name surely has decided advantages over the somewhat vague term of minette of the older systems.

MONCHIQUOSE (ANALCITE-BASALT).

Introductory.—There exists in the Highwoods a vast number of dikes; indeed, no geologic feature is more characteristic of the group, as has been already explained and shown on the geologic map. Of these dikes a very great number belong to the type about to be described; their field occurrence and characters have been described on pages 31–36.

The rocks of this type were thoroughly investigated by Lindgren,[b] who showed that they contain analcite as a prominent component and under such conditions and with such associations that he was compelled to regard it as a primary mineral. The author, in the subsequent study of these rocks and of closely related types from other localities in Montana, agreed with Lindgren and published a paper,[c] in which Lindgren's ideas were brought out and supported by additional evidence, but it should be remembered that Lindgren first recognized analcite as a possible primary component of igneous rocks, gave the proofs which demonstrate it, and offered the explanation of its mode of formation under such circumstances.

[a] Chemical analyses of igneous rocks: Prof. Paper U. S. Geol. Survey No. 14, 1903, p. 347.
[b] Eruptive rocks from Montana; Proc. California Acad. Sci., ser. 2, vol. 3, 1890, p, 51.
[c] The monchiquites or analcite group of igneous rocks; Jour. Geol., vol. 4, 1896, p. 679.

Since Lindgren's original paper, which was brief and wanting in some details, is inaccessible to many petrographers, and the study of more abundant and widely distributed material from the Highwoods has brought out new facts, a full description of this type, based partly on Lindgren's studies and partly on those of the author, is given, together with an analysis and a discussion of its position in the new system of classification.

Megascopic characters.—On a freshly fractured surface these rocks are generally a dark greenish black, varying into olive or grayish tones. They are at times thickly dotted with phenocrysts of a stout, well-developed black or greenish-black augite which attains a length of 10 mm. They are also abundantly spotted with round white phenocrysts attaining a diameter of 1 to 2 mm. Rarely small flecks of biotite are visible and sometimes greenish grains of olivine. Sometimes the augite is very conspicuous as a phenocryst and the white crystals are rare; sometimes the reverse is true, the latter are extremely abundant, and the rock assumes a dark-gray color. In the majority of cases both are abundant. Thus in the variance of these two phenocrysts two extremes connected by all degrees of transition are seen. In the geologic description of these rocks in a previous chapter it was stated that the dikes of the region could be divided into three types, one containing prominent phenocrysts of biotite, to which the field name Highwood minette or mica trap could be given and which have been described petrographically as biotite-cascadose; one with phenocrysts of augite (augite-porphyry or augitophyre), and one with phenocrysts of analcite (analcite-basalt). These last two are the extremes of the type under consideration, and although megascopically there is considerable difference between them, petrographically they are the same, their appearance depending on the relative proportions of the augite and white mineral (analcite) which develop as phenocrysts or remain in the groundmass.

Microscopic characters. In thin section the following minerals are seen: Iron ore, apatite, biotite, olivine, augite, and analcite. The iron ore and apatite offer nothing deserving mention. "The olivine is usually sharp edged, clear, and fresh, sometimes surrounded by a narrow border of biotite. When decomposing, a yellowish brown ferruginous serpentine results. A mineral of the spinel group is observed as an inclusion in the olivine."[a]

The augite is of the usual Highwood type, of a pale-green, nonpleochroic color, well crystallized. It often becomes darker green toward the border, from increase, no doubt, of ægirite. The extinction angle is very wide, up to 45° or more, the cleavage good. Forms observed commonly (110), (011), (100), and (111). Twinning on (100) rather common. There is great variation in size from the largest crystals

[a] Lindgren, op. cit., p. 53.

noted to the small microlites of the groundmass. It frequently contains inclusions of glass and magnetite.

In regard to the analcite Lindgren states:

It appears embedded in the groundmass in hexagonal, seldom octagonal—most frequently simply rounded—sections. In size they do not exceed one millimeter, and are frequently much smaller. Most of the crystals are perfectly isotropic, but not quite clear, being clouded somewhat by minute interpositions, which, under large magnifying power, prove to be largely gas, in part also glass inclusions. The former have often a very irregular form. Irregular spots showing a faint double refraction are sometimes noted, more in some sections than in others. Under favorable circumstances an imperfect cleavage in two directions crossing each other perpendicularly may also be noticed. Minute fragments from an exceptionally large crystal melt rather easily and quietly before the blowpipe to a white enamel. In one thin section a large crystal showing irregular octagonal form with very distinct cleavage was selected for experiment. It was uncommonly clear and perfectly isotropic. Hydrochloric acid dissolves it easily upon very slight heating under abundant formation of chloride of sodium. Ignition does not make it opaque and does not produce double refraction. No microscope reaction for Cl or SO_3 could be obtained.

The groundmass of these rocks, in which the above minerals are embedded, consists of minute dark prisms of augite, grains of iron ore, and small analcite crystals, which form a colorless background upon which everything else is displayed. Lindgren remarks with truth that glass is probably not present. Under the conditions in which rocks of such chemical composition have formed it does not seem that glass could be present, any more than in a typical granite.

Discussion of analcite.—That the isotropic mineral described above is actually analcite was shown by Lindgren by the separation of it by heavy fluids and by the analyses of the product obtained. This was performed on two samples, with the results given in I and II of the appended table.

Analyses of analcite.

	I.	II.	III.	IV.
SiO_2	54.90	49.87	52.38	0.873
Al_2O_3	23.30	22.55	22.92	.225
Fe_2O_3	Trace.	1.51	.75	.005
CaO	1.90	2.62	2.26	.041
MgO	.70	1.28	.99	.025
Na_2O	10.40	10.92	10.66	.173
K_2O	1.60	2.66	2.13	.022
H_2O	7.50	11.05	7.50	.417
Cl	None.	Trace.		
SO_3	None.	None.		
Total	100.30	102.46	99.59	

Since these analyses were made on very small quantities the ordinary analytical errors become appreciable, and therefore the average of the two would undoubtedly be more correct than either alone, as the errors would tend to balance one another. The determination of water in II was made on only 0.1 gram and is evidently too high, and may be excluded. The average is shown in III and its molecular ratios in IV. The lime, iron, and magnesia are due to admixed microlites of pyroxene, and deducting sufficient silica to turn them into a silicate of the general formula $RO.SiO_2$ the remaining ratios have the following relation:

SiO_2	0.802 =	4.00 =	4
Al_2O_3	.225 =	1.12 =	1
K_2O+Na_2O	.195 =	.97 =	1
H_2O	.417 =	2.08 =	2

This gives the analcite formula Na_2O, Al_2O_3, $4SiO_2$, $2H_2O$, some of the soda being replaced by a little potash, as often happens.

It is thus shown that the products obtained by Lindgren and analyzed by Melville were undoubtedly analcite; but the author has been interested to discover, if possible, whether leucite might also be present. As mentioned by Lindgren, it is clear that the material is not sodalite or nosean, and its form precludes an alteration from nephelite. On the other hand, it has been shown on a previous page, under the heading "Leucite-shonkinose," that in the fresh rock of the East Peak stock both leucite and analcite occur simultaneously, and reasons are given for considering the latter a primary mineral. Under the microscope leucite might be present and not distinguishable from analcite.

For this purpose a specimen from a dike on Arrow Peak was selected which corresponds very closely with the foregoing description of the type. The isotropic phenocrysts are of a very pale-brownish tone, and some of them have a few tiny inclusions of iron ore arranged in one or two concentric circles, suggesting the arrangement seen in leucite. Under crossed nicols occasional spots of faint double refraction were seen. These suggestions of leucite caused the selection of the sample. All the other minerals are perfectly fresh and normal.

The rock was crushed, sifted, the dust washed out by suspension in distilled water, and after a large amount of magnetite had been extracted with the magnet the powder was placed in the potassium mercuric iodide solution. The specific gravity of the solution was then regularly lowered and determined, and the resulting precipitates collected and examined. At first, of course, all the pure augite and remaining magnetite fell, and after this the same minerals containing some white material were precipitated. The succeeding precipitates were as follows:

No. 1. Specific gravity, 2.56; very little, impure.
No. 2. Specific gravity, 2.52; very little, impure.
No. 3. Specific gravity, 2.45; very little, impure.
No. 4. Specific gravity, 2.40; some, lighter in color.
No. 5. Specific gravity, 2.36; more, purer.
No. 6. Specific gravity, 2.32; large amount, quite pure.
No. 7. Specific gravity, 2.28; nearly all the remainder, very pure.

The first four portions were very small in amount and were contaminated with particles of the dark femic minerals, chiefly augite. These became less, but not until 2.36 was reached did they practically disappear. It was thought that if at 2.45 anything came down in noticeable amount it could be analyzed and the question whether it was leucite be determined. From 2.56 to 2.36, however, the portions obtained were entirely too small and impure for analysis; they evidently consisted of compound grains of substances above 2.56 and below 2.36, which were mingled in varying proportions and gradually fell as the specific gravity of the liquid was lowered. Below 2.32 a pure product was left which contained by far the greater part of the white salic component of the rock. The analyses in Lindgren's work render it unnecessary to make a new one of this material; it can be nothing else than analcite, and as qualitative tests showed water, soda, and alumina as its main constituents, this point may be regarded as settled.

As the result of this examination, then, it can be said with confidence that in the sample selected analcite is certainly the dominant mineral, and leucite can be present in only very minute amounts, if at all; therefore, Lindgren's conclusion that in dikes in the Highwoods there is a rock type composed of augite, iron ore, olivine, and analcite, with these minerals all fresh and all crystallized in their own characteristic forms, is confirmed.

In the author's opinion it would not be correct to conclude that necessarily all the rocks which show round white phenocrysts, and which are so abundant in the Highwoods, are pure analcite rocks. The analysis of a specimen from Highwood Gap shows a considerable amount of potash, and no mineral which might contain potash except leucite or its alteration products. The same is true for the basaltic surface lavas described later. Furthermore, the sheets about Square Butte and the Shonkin Sag laccolith, which megascopically and microscopically are similar to the rocks under discussion, are very evidently intruded portions of the shonkinite magmas of those occurrences whose textural development has been determined by the physical conditions attending their crystallization and solidification.

Their white phenocrysts should be regarded in large part as pseudoleucites. Regarding this rock, Lindgren says:[a]

In some specimens of the rock in question the larger part of the colorless mineral is faintly doubly refracting, showing bluish gray colors between crossed nicols. The crystals are then not so well defined and often take the form of rounded spots separated by the groundmass and small porphyritic augites and olivines. These rounded spots between crossed nicols divide into irregular, sometimes also regular, triangular fields. I regarded this (see Vol. XV, Tenth Census U. S.) as double refracting analcite. When isolated it has the specific gravity of analcite and, according to an analysis of impure material, a similar composition, although the percentage of silica is too low. No chlorine or sulphur. Specific gravity, 2.24.

It should be noticed that the rocks in which this variety occurs are perfectly fresh, even more so than those containing the isotropic mineral; the olivine and augite show no trace of decomposition.

In the analcite-basalts, as described here, there is no evidence of decomposition, except that the olivine is occasionally converted into yellowish brown serpentine. In other specimens, however, it is seen that the analcite offers but slight resistance to decomposition. Needles of a zeolite with vivid colors of interference, probably stilbite, penetrate the analcite in all directions, and soon every crystal is transformed into an aggregate of zeolites. Large stilbite crystals are found in the decomposing rock. The augite is much more resistant and frequently remains intact when all the other constituents have been entirely decomposed.

The author is inclined to believe that these doubly refracting areas are in part pure analcite, in part pseudoleucites, and the zeolitic alteration proceeds in both, the zeolite being perhaps in part stilbite, but also in large part natrolite and possibly other zeolites as well.

In summation the author believes that some of these rocks, which appear so much alike in hand specimens, are pure primary analcite-basalts; some are primary analcite- and leucite-basalts, and in some these minerals have suffered secondary zeolitic and pseudomorphic alterations. He sees no reason why primary analcite and leucite should not be present in the same rock. It is difficult to imagine how part of the leucite should have changed to analcite and part not, if all the minerals are otherwise fresh, and the crystal form and occurrence of the analcite negatives the view that it is secondary after any other mineral (see p. 111).

The primary nature of analcite as a rock-forming mineral, brought out by Lindgren and the author, has been recognized by many petrographers,[b] and its occurrence and mode of formation are so thoroughly

[a] Proc. California Acad. Sci., 2d ser., vol. 3, p. 56.

[b] Cross, Analcite-basalt from Colorado: Jour. Geol., vol. 5, 1897, p. 684.
Washington, Am. Jour. Sci., 4th series, vol. 6, 1898, p. 182.
Brögger, Ganggefolge des Laurdalits, 1897, p. 103.
Card and Mingaye, Records Geol. Surv. New South Wales, 1902, vol. 7, pt. 2, p. 93.
Evans, Quart. Jour. Geol. Soc., vol. 57, 1901, p. 38.
Ogilvie, Jour. Geol., vol. 10, 1902, p. 500.
Lacroix, Roches alcalines d'Ampasindava: Nouv. Arch. du Muséum, 4th series, vol. 1, 1902, p. 197.
Pirsson, Am. Jour. Sci., 4th series, vol. 13, 1902, p. 161.

discussed that further reference to this point is unnecessary. The writer would only remark, in passing, that this view must not be carried too far, and that while some analcite seems undoubtedly primary, a great deal must undoubtedly be secondary. There is presumably a stage in rock crystallization where, as the earlier components are separated, there gradually results a mother liquor composed of silica, alumina, alkalies, and water, which will crystallize into feldspars, feldspars and quartz, or feldspathoids and analcite, with partial or complete exclusion of the water vapor, according as proportions and conditions vary. The transition is not sharp between this stage and that where the attacking of the earlier components by the excluded vapors with formation of new minerals (pneumatolytic stage) probably begins. The view as to whether certain compounds are primary or secondary must in many cases be largely a subjective one. The general view is that secondary minerals are those formed from previously existent ones, but how shall we classify those formed from a glass—by devitrification proceeding from aqueous vapors?[a]

Chemical composition.—To determine the chemical composition of these rocks and their relation to the other magmas of the region, a fresh example of average type from a dike on the east side of the very summit of the divide in Highwood Gap was analyzed by Doctor Foote, with the results given in I. Two analyses of similar rocks from the neighboring Little Belt Mountains are given for comparison, and it will be seen that chemically they are very much like this rock. Some other analyses from other petrographic areas also show a strong general resemblance. The analysis of the dark rock of the Shonkin Sag laccolith is presented for comparison of the shonkinoid magmas of the Highwood area. They are much alike except in the relations of the alkalies.

[a] This inquiry becomes more pertinent since Morozewicz, in a very complete and able investigation of some monchiquoid rocks (Ganggesteine des Bezirk's von Taganrog: Mem. du Com. Géol. St. Petersburg, vol. 8, 1903, p. 45), suggests that the analcite which they contain is produced by the weathering of a glass which happened to have the composition of analcite, minus the water. This interesting paper reached the writer after this bulletin had been handed in for publication, and he regrets that he is able only to notice it by this note in the revision.

Analyses of monchiquose (analcite-basalt) and related rocks.

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.
SiO_2	47.82	48.39	48.35	45.59	41.10	43.39	47.83	0.797
Al_2O_3	13.56	11.64	13.27	12.98	14.82	16.67	12.10	.131
Fe_2O_3	4.73	4.09	4.38	4.97	2.35	3.47	3.53	.030
FeO	4.54	3.57	3.23	4.70	10.38	8.80	4.80	.063
MgO	7.49	12.55	8.36	8.36	9.43	7.30	8.64	.187
CaO	8.91	7.64	9.94	11.09	10.56	8.79	9.35	.159
Na_2O	4.37	4.14	3.35	4.53	3.94	3.30	2.94	.070
K_2O	3.23	3.24	3.01	1.04	1.28	2.17	5.61	.034
H_2O+	3.37	2.56	2.89	3.40	2.31	2.67	1.52	.187
H_2O-		.28	.90	.51	.39	.29	.70	
CO_2		None.	.30		.26	.39	.12	
TiO_2	.67	.73	.52	1.32	3.20	2.20	.77	.008
P_2O_5	1.10	.45	.40	.91	.19	.41	1.11	.008
SO_3	Trace.	.08			.09	.19	None.	
Cl	.04	Trace.		.05	Trace.	.02	Trace.	
Cr_2O_3		.07	Trace.		Trace.	Trace.	.04	
NiO		None.	.04		Trace.	Trace.	Trace.	
MnO	Trace.	Trace.	.19	.14	.14	.19	.15	
BaO	.16	.32	.54	.13	.06	.02	.46	
SrO	.21	.15	.09	.12	Trace.	Trace.	.13	
Fl			.25				.05	
ZrO_2				.03			.03	
	100.20	99.90	100.01	99.87	100.50	100.28	99.99	
O=F			.11					
Total			99.90					

I. Monchiquose (analcite-basalt) from dike on east side Highwood Gap. H. W. Foote, analyst.

II. Analcite-basalt from Bandbox Mountain, Little Belt Mountains, Montana. W. F. Hillebrand, analyst. Twentieth Ann. Rept. U. S. Geol. Surv., pt. 3, 1900, p. 545.

III. Monchiquose (analcite-basalt) from Big Baldy Mountain, Little Belt Mountains, Montana. W. F. Hillebrand, analyst. Loc. cit., p. 548.

IV. Monchiquose (analcite-basalt) from The Basin, Cripple Creek, Colorado. W. F. Hillebrand, analyst. W. Cross, Jour. Geol., vol. 5, 1897, p. 689.

V. Analcite-basalt from Fernhill dike, Sydney, New South Wales. H. P. White, analyst. Records Geol. Surv. New South Wales, 1902, vol. 7, p. 93.

VI. Analcite-basalt from Bondi boss, Sydney, New South Wales. J. C. H. Mingaye, analyst. Loc. cit.

VII. Montanose (shonkinite) from Shonkin Sag laccolith, Highwood Mountains. W. F. Hillebrand, analyst.

VIII. Molecular proportions of I.

Mineral composition or mode.—The mineral composition can be found by calculation from the analysis. It is as follows:

Mineral composition or mode of monchiquose.

Leucite	14.8
Analcite	30.0
Augite	35.2
Olivine	8.0
Iron ore	8.2
Apatite	2.6
Rest	1.2
Total	100.0

Classification in prevailing systems.—In these, if one follows the law of priority, Lindgren's name should stand and this rock would be termed analcite-basalt, or if leucite is also present, as in the above, analcite-leucite-basalt. In Rosenbusch's system its occurrence in lamprophyric dikes must be taken into account, and the rock falls into the camptonite-monchiquite-alnöite series and would be an analcite-leucite-monchiquite.

Classification in the new system.—In this its systematic position is seen in the following computation of its norm and position:

Calculation of the norm of monchiquose.

	Analysis.	Molecular ratio.	Or.	Ab.	Ne.	So.	An.	Di.	Ol.	Mt.	Il.	Ap.
SiO_2	47.82	0.797	204	204	68	3	56	210	53			
Al_2O_3	13.56	.131	34	34	34	1	28					
Fe_2O_3	4.73	.030								30		
FeO	4.54	.063						12	13	30	8	
MgO	7.49	.187						93	94			
CaO	8.91	.159					28	105				26
Na_2O	4.37	.070		34	34	2						
K_2O	3.23	.034	34									
TiO_2	.67	.008									8	
P_2O_5	1.10	.008										8
Cl_2	.04	.001				1						
Rest	3.74		34	34	34	1	28	105	53	30	8	8

Or	18.9	54.7
Ab	17.8	
An	7.8	
Ne	9.7	
So	.5	
Di	23.4	42.1
Ol	7.9	
Mt	7.0	
Il	1.2	
Ap	2.6	
Rest	3.7	
Total	100.5	

Class, $\frac{\text{Sal.}}{\text{Fem.}}=\frac{54.7}{42.1}=1.3$=III, salfemane.

Order, $\frac{L}{F}=\frac{10.2}{44.5}=0.23$=lendofelic=6, portugare.

Rang, $\frac{K_2O'+Na_2O'}{CaO'}=\frac{104}{28}=3.7$=domalkalic=2, monchiquase.

Subrang, $\frac{K_2O'}{Na_2O'}=\frac{34}{70}=0.49$=dosodic=4, monchiquose.

The texture is eminently porphyritic; the mode is abnormative, with analcite as the critical mineral; the rock may thus be termed phyro-analcite-monchiquose. If it is thought desirable to indicate that both salic and femic phenocrysts are present the rock may be termed salfemphyro-analcite-monchiquose. This is a very concise expression to indicate a rock which consists of about equal proportions of light and dark minerals, which has a certain general chemical composition, in which the ordinary silico-aluminous alkalic minerals are replaced by analcite, and which has a porphyritic texture with phenocrysts of analcite and augite.

PETROGRAPHY OF EXTRUSIVE FLOWS, BRECCIAS, AND TUFFS.

GENERAL PETROGRAPHIC DESCRIPTION.

The extrusive rocks occurring in the Highwoods are readily divided into two groups—the light-colored feldspathic salic rocks, which for field purposes have been roughly classed as andesites, and the dark augitic rocks or basalts.

Feldspathic lavas and tuffs.—Those of the first group are dense rocks of a very light color, usually a pale brown inclining to gray, sometimes a light gray. Close examination shows that they are very apt to contain streaky portions or broken angular fragments whose form is distinguished by a slightly different color or texture from the inclosing matrix. These are clearly flow breccias—portions of the lava which after having solidified have been broken again by movements of the viscous mass and kneaded through it without remelting. Close inspection of them also shows in many cases small black shining specks, minute crystals of an iron-bearing mineral.

When these rocks have been greatly weathered and perhaps subjected to heat and steam from later effusions of lava, they assume darker colors with reddish tones, owing to the oxidation of the iron mineral, and in some such cases—as, for instance, at the head of Little Belt Creek and on upper Briar Creek—they are of a strong, almost brick, red color.

Where ash beds or fine tuffs of these feldspathic lavas occur, as on the Middle Peak divide, they have the same light-gray color, but are even and dense and are indurated to very dense compact rock masses, often with a platy structure; in these cases they are not easily distinguished from fine-grained, light-colored sandstones.

Basaltic lavas.—Basaltic lavas occur in a much greater variety of forms than the preceding. They appear as dense and compact, either with or without embedded porphyritic minerals, as amygdaloids, as scoriaceous lava, and as conglomerates or breccias.

The compact basalts are in places black or greenish-black rocks, as on the Pinewood Peak saddle; at other places they are dark stone gray and sometimes platy, as on Arrow and Lava peaks. As they become lighter in color the embedded minerals or phenocrysts make their appearance. The rocks are sometimes thickly stippled with tiny white specks of what is generally an altered leucite, or pseudoleucite. They have a pin-pricked appearance, resembling certain well-known leucite-bearing rocks of the Eifel district in Germany. In other examples these pseudoleucites are much farther apart and much larger, having the size of medium-coarse shot. They are regularly sprinkled through the rock and many dark-green prisms of augite accompany them. A gray-colored example of this type collected on the upper slopes of the basin west of the Arnoux stock, whose waters flow into Shonkin Creek opposite North Peak, so exactly resembles specimens of the leucitophyre of Rieden by the Laacher See in the Eifel district of Germany that one can scarcely be distinguished from the other.

Amygdaloidal basaltic lavas.—The amygdaloidal lavas vary in color from medium to dark gray; in some cases the amygdules are as large as hazelnuts, but generally they are about the size of peas and are rather thickly scattered through the rock. They are solid and composed of fibrous zeolites, usually natrolite and stilbite. Sometimes they are flattened ovoids arranged in layers and lines showing movement which occurred in the viscous mass before the formation of the zeolites and which drew out and extended the steam pores in which the zeolites were subsequently deposited. This type of lava is common in the masses composing Lava and Arrow peaks.

In another type the amygdules are about the size of small shot and thickly scattered through the rock. They are white and so closely resemble the pseudoleucite phenocrysts that except on very minute inspection it is difficult to tell them apart. The lens shows that they are gray with a faint pink tone and fibrous, while the pseudoleucites are greenish and granular. This type is found abundantly on Pinewood Peak.

In all of these amygdaloidal lavas the rock is more or less altered; if olivine occurs it is converted into a dark-red opaque substance; often the augites are changed, but they appear to have withstood the action of the heated waters and vapors and weathering better than any of the other original minerals.

Scoriaceous basaltic lavas.—These are closely related to the foregoing, differing only in that the steam cavities are not filled with zeolites. The slopes of Arrow and Lava peaks are composed largely of a débris of fragments of scoriaceous and at times almost pumiceous vesicular lava, varying in color from dark stone gray to deep mahogany red. The only definite recognizable mineral to be seen in this material is the augite in black glittering prisms.

While part of it may be the upper surface of flows, a large portion of it is projected matter, varying from ash and lapilli to bombs of considerable size.

Basaltic tuffs and breccias.—These are dark-colored rocks, sometimes dark gray or dark brown, but commonly of a chocolate color. The tuffs or ash beds are fine in texture and compact, showing considerable induration; they have a dull, hackly fracture, on whose surfaces are many glimmering points of light reflected from minute fragments of crystals. The breccias are made up of the same material, but embedded in them are innumerable bits of rock, some angular, others somewhat rounded. Among these the most common are pieces of baked, reddened, and hardened shale, and of the leucitic lavas previously mentioned. The included chunks are of all sizes up to a foot or so in diameter. In some cases, as in material collected on upper Highwood Creek about a mile north of the Highwood Gap divide and near the large wall dike, the inclosed pieces are rounded sufficiently to produce the appearance of a volcanic conglomerate.

The ash beds and breccias described are found all over the eastern and northern parts of the mountains and as isolated or prolonged patches among the sedimentary foothills, as on upper Davis and Aspen creeks.

For the purpose of detailed investigation of the petrographic character of the rocks composing the effusive masses, types of the feldspathic and basaltic lavas described above have been selected for study and analysis—in each case the freshest and best material that could be found. The greater part of the ejected Highwood matter is unsuited by various processes of alteration for petrographic investigation, but in a considerable number of instances reasonably fresh material of both kinds was found. The study of the thin sections has shown that, from the standpoint of advanced classification, practically only two types are present, as already roughly determined in the field and shown on the geologic map.

The sections show, it is true, a slight variation in the specimens collected from different parts of the field, as will be mentioned later, but nothing that would warrant further separation. Under prevailing systems of classification the types would be latite (trachyandesite) and leucite-analcite-basalt; under the new system they are adamellose and shonkinose.

TRACHIPHYRO-HORNBLENDE-ADAMELLOSE (LATITE OR TRACHYANDESITE).

Occurrence.—The best appearing material of the lighter colored feldspathic lavas was found on the north side of the upper reaches of North Willow Creek as it issues from the mountains. As may be seen by reference to the geologic map, the feldspathic lavas are prolonged in this direction outward from the mountain mass and form bold projecting masses and crags. On these exposed surfaces the effusive character of the material is clearly shown by flowage lines which dip away from the mountains and have the wavy, twisting nature so often seen in lavas. At the same time the rock has a clearly brecciated character, angular chunks of various sizes being brought out in the weathering. The appearance indicates clearly that it is a flow breccia, the first cooled and solidified crust having been broken up and rolled in angular fragments through the still viscous moving mass.

Megascopic characters.—On a broken surface the rock is a pale-purplish brown or light-chocolate color spotted with angular fragments of a slightly different tone of the body color, but in some cases of a dull gray. The contrast and the brecciated character are not marked. The fragments on the average are of about the size of a hazelnut. The rock is dotted with small dark specks of a ferromagnesian mineral which often shows a lustrous cleavage surface.

Microscopic characters.—In thin section the microscope discloses the following minerals: Iron ore, apatite, hornblende, biotite, labradorite, alkali feldspar, quartz (?), and glass.

Iron ore is not common. It occurs in the usual small grains and is more abundant in some brecciated areas than in others. The apatite is seen in the common small prismatic crystals and shows no especial features.

The hornblende is very abundant, though it occurs in greater quantity in some areas than in others. It occurs in short, stout prisms, bounded, when well crystallized, by 110, 010, and 111; long slender ones are rare. The cleavage, as usual, is marked. It has a rather striking and remarkable color and pleochroism.

$\mathfrak{c}$=deep orange-red, inclining to brownish in some specimens.
$\mathfrak{b}$=orange.
$\mathfrak{a}$=pale to lemon-yellow.

The inclination to brownish tones is somewhat variable, not only in the different specimens but according to the strength of the illumination. It is to be noted that these colors are deepest in those specimens which, by reason of a ferruginous pigment distributed through them, have megascopically strong reddish tones. Since the mineral appears uniform and homogeneous, it is difficult to think that the color is the result of alteration or staining; on the other hand, the hornblende is of the common green variety in specimens collected at the little canyon of Highwood Creek above the Cretaceous part of its valley, near the Shonkin stock, and at the head of Little Belt Creek on the south slopes of Pinewood Peak. At the last-named locality the green crystals contain occasional spots of the red type, so that from the evidence at hand it does not appear certain whether the more common red kind is an alteration of the green or not. In this connection it is of interest to note that where the hornblende is deep red the biotite, which is a rare constituent occurring in small phenocrysts like the hornblende, also shows so nearly the same colors in its pleochroism that it is distinguished from the hornblende with difficulty. In the red variety the angle *c* on $\mathfrak{c}$ is nearly zero and the double refraction is not very strong.

The labradorite is the next most striking mineral. It does not occur as a phenocryst, but is confined to the groundmass, where it appears as short laths which vary in size, ranging from some that are almost as large as small phenocrysts to very minute ones. Carlsbad and albite twinning are common and afford excellent sections for determining the ratios of An to Ab. A number of measurements showed that Ab_3An_4 is the labradorite present; there were one or two which gave Ab_7An_8. These laths are in some cases bent in the viscous flow structure.

The alkali-feldspar appears also in small laths and in fragments distinguished from the labradorite by lack of twinning, lower birefringence, and parallel extinction. The sections are too small for detailed observations.

This mesh of interwoven minerals is surrounded by films of a low or nonpolarizing substance. In some cases, especially around the alkali-feldspar sections, high powers show "pepper and salt" mantles, which might have become micrographic or micropoikilitic areas if the scale on which they crystallized had been larger; these areas resemble devitrified acid (quarfelic) glasses in appearance. In other places these mantles are not seen, and the whole arrangement suggests a final remnant of glass in the quickly crystallizing flow which has since then partially devitrified in places, giving rise to quartz and alkali feldspar, though the scale is too small for direct proof.

To make sure that a feldspathoid was not present instead of glass, the rock was treated with nitric acid, but no gelatinous silica could be obtained.

Varieties of the type.—In the different specimens collected are some variations which are worth noting. Those in the hornblende have been described above. In the material from the head of Little Belt Creek was observed some quartz in scattered angular pieces; the labradorite appears more distinctly as a phenocryst, and the groundmass is more largely composed of the "pepper and salt" aggregate of minute quartz and alkali feldspar. In some specimens from Briar Creek a few crystals of sporadic augite well crystallized and of a brownish tone were noted; augite occurs also in the acidic (perfelic) extrusive material at the debouchment of Highwood Creek previously mentioned, and the groundmass of this rock is more felt-like than in the one last described, though it is still exceedingly minute. The material from the Shonkin stock has rather more feldspar and less hornblende.

Mineral composition or mode.—The mineral composition was ascertained by Rosiwal's method. The fine feldspars could not, however, be measured separately, and all of the feldspar was therefore lumped into areas and the glass or residual material was included. Two traverses, *a* and *b*, give the following results. It will be noticed that biotite was observed only once, and therefore constitutes an unimportant constituent. The very fine needles and tiny granules of apatite could not well be measured and were disregarded. The analysis proves that 0.7 per cent must be present. The chief value of the determination is that it shows the relation between the hornblende and the feldspars.

Table showing the calculation of the mode of adamellose.

	Iron ore.	Horn-blende.	Feldspar, etc.	Biotite.	Total.
$a, \frac{mm.}{100}$ meas	21	159	1,024	6	1,210
$b, \frac{mm.}{100}$ meas	26	228	1,088	0	1,342
$a+b, \frac{mm.}{100}$ meas	47	387	2,112	6	2,552
a, No. meas	15	43	50	1	109
b, No. meas	17	54	56	0	127
a+*b*, No. meas	32	97	106	6	236
a, per cent	1.7	13.1	84.6	0.5	99.9
b, per cent	1.9	16.9	81	0	99.8
a+*b*, per cent	1.8	15.1	82.7	0.3	99.9

It is impossible to determine the relative amounts of plagioclase, orthoclase, and quartz or glass, and these must be taken collectively.

Chemical composition.—This is shown in I of the following table of analyses. It is like many andesoid rocks, but the considerable amount of potash is to be noted. Since biotite and other potash-bearing silicates are absent, except orthoclase, there must be about 25 per cent of that mineral present, or at least capable of forming. Compared with similar rocks of other regions, the only one that closely resembles it with regard to adamellose is the one from Thibet described by Bäckström. The type that seems to be most like it chemically is one on the border between monzonose and adamellose, shown in III. Under the name "vulsinite" Washington described Italian lavas which contained abundant labradorite in addition to the alkali feldspars of trachytes, and which mineralogically resemble the present rock. An analysis of one of these is shown in IV. Like the Willow Creek rock, the rock contains considerable lime and potash. Ransome proposed the term "latite" for all effusive rocks "standing chemically about midway between the andesites and trachytes;"[a] this definition would include the Willow Creek rock. An analysis of a typical latite is shown in V, and it has an essential resemblance to the other analyses.

If this effusive is compared with any of the granular deep-seated

[a] Loc. cit. infra., p. 375.

masses of the district, the one to which it has the nearest resemblance is the shoshonose or monzonite of Highwood Peak. The latter is a less siliceous rock and contains more lime, iron, and magnesia. The material around Pinewood Peak unquestionably belongs to the Highwood Peak center of eruption, and this type thus stands as intermediate between the shoshonose or monzonite and the pulaskose or syenite, and represents a less differentiated stage than either of them. This would tend to show that it is also older, and when one considers the relative geologic and topographic positions of the rock masses this idea appears to be confirmed.

Analyses of adamellose or trachyandesite and related rocks.

	I.	II.	III.	IV.	V.	VI.	VII.
SiO_2	59.24	61.45	57.04	55.69	56.78	51.00	0.987
Al_2O_3	13.84	14.36	13.66	19.08	16.86	17.21	.134
Fe_2O_3	5.46	2.75	4.96	4.07	3.56	2.41	.034
FeO	1.36	4.61	1.77	3.26	2.93	4.23	.019
MgO	4.79	2.73	4.43	3.41	3.41	6.19	.120
CaO	5.60	4.34	6.23	6.87	6.57	9.15	.100
Na_2O	3.13	3.98	3.08	2.89	3.19	2.88	.050
K_2O	4.22	3.75	4.95	4.41	3.48	4.93	.044
H_2O+	2.02	.87	1.10	.17	1.21	.63	.112
H_2O-	------	------	1.11	------	.15	------	------
TiO_2	.22	1.37	.94	------	1.15	.13	.003
P_2O_5	.34	------	.63	------	.42	.33	.002
SO_3	.08	------	------	------	------	.14	------
Cl	.04	------	------	------	------	Trace.	------
MnO	Trace.	------	.17	Trace.	------	Trace.	------
BaO	Trace.	------	.22	------	------	.34	------
SrO	------	------	Trace.	------	------	.14	------
	------	------	NiO .07	------	CO_2 .18	------	------
Total	100.34	100.21	100.36	99.85	99.89	99.60	------

I. Adamellose (trachyandesite) from North Willow Creek, Highwood Mountains, Montana. E. B. Hurlburt and B. Barnes, analysts.

II. Adamellose (bronzite-andesite) from Thibet. H. Bäckström, analyst. (Pet. Mitt., Erg. Hft. No. 131, p. 2.)

III. Monzonose-adamellose, (mica-basalt), from Santa Maria basin, Ariz. W. F. Hillebrand, analyst. Iddings, Bull. Philos. Soc. Wash., vol. 12, 1892, p. 212.

IV. Shoshonose (biotite-vulsinite) from Monte Santa Croce, Rocca, Monfina, Italy. H. S. Washington, analyst. Jour. Geol., vol. 5, 1897, p. 252.

V. Shoshonose (augite-latite) from Clover Meadow, Tuolumne County, Cal. G. Steiger, analyst. Ransome, Am. Jour. Sci., 4th series, vol. 5, 1898, p. 363.

VI. Shoshonose (monzonite) from Highwood Peak. E. B. Hurlburt, analyst.

VII. Molecular proportions of I.

Texture.—This has been partly indicated in the foregoing. Megascopically these rocks are firm, compact, and between the trachytic and felsitic in character, and they are porphyritic only on close inspection. They are actually microtrachytic and almost microporphyritic.

Classification in the new system.—The position of this type in the new classification is found in the following calculation of its norm:

Calculation of the norm of adamellose.

			Or.	Ab.	An.	Di.	Hy.	Mt.	Il.	Ht.	Ap.	Qtz.
SiO_2	59.24	0.987	264	300	80	106	67					170
Al_2O_3	13.84	.134	44	50	40							
Fe_2O_3	5.46	.034						16		18		
FeO	1.36	.019						16	3			
MgO	4.79	.120				53	67					
CaO	5.60	.100			40	53					7	
Na_2O	3.13	.050		50								
K_2O	4.22	.044	44									
TiO_2	.22	.003							3			
P_2O_5	.34	.002									2	
H_2O, etc	2.14											
Total	100.34		44	50	40	53	67	16	3	18	2	170

Or	24.5	72.0
Ab	26.2	
An	11.1	
Qz	10.2	
Di	11.4	25.8
Hy	6.7	
Mt	3.6	
Il	.5	
Ht	2.9	
Ap	.7	
Rest	2.1	
Total	99.9	

Class, $\frac{\text{Sal.}}{\text{Fem.}}=\frac{72.0}{25.8}=2.8=$II, dosalane.

Order, $\frac{Q}{F}=\frac{10.2}{61.8}=0.17=$quardofelic$=4$, austrare.

Rang, $\frac{K_2O'+Na_2O'}{CaO'}=\frac{94}{40}=2.3=$domalkalic$=2$, dacase.

Subrang, $\frac{K_2O'}{Na_2O'}=\frac{44}{50}=0.88=$sodipotassic$=3$, adamellose.

The comparison of the norm with the mode shows that the diopside and hypersthene of the norm, and perhaps also some of the iron ore and soda (i. e., albite), are replaced in the mode by hornblende. The amounts do not exactly correspond, but this is probably due to the fact that in diopside a much larger amount of lime is needed than in hornblende, and in the mode this lime appears as anorthite. The alumina needed for anorthite might be supplied from albite, the soda of the latter going into the hornblende with iron. On account of the 15 per cent of the alferric mineral hornblende, the mode is an abnormative one.

The textural characters have been already given; they are expressed by the term trachiphyro. In the new system the rock should therefore be termed trachiphyro-hornblende-adamellose.

Classification in prevailing systems.—Casual study of this rock under the microscope alone would determine it as a hornblende-andesite. When the analysis is considered and it is perceived how much of the orthoclase molecule must be present, it can not be considered a typical andesite, but must assume an intermediate position between the andesites and trachytes, and is therefore a trachyandesite, or, if Ransome's proposed term be employed, a hornblende-latite.

PHYRO-SHONKINOSE (ANALCITE-LEUCITE-BASALT).

Occurrence.—Perfectly fresh unchanged material of the basaltic extrusives has not been found in the area. The difficulty in some cases of distinguishing between the outcrops of dikes and the effusives which they cut has been previously alluded to. The dikes are not far from the original surface, and there was no marked difference in physical conditions, consequently in minerals and texture they closely resemble the flow rocks, to which no doubt they gave origin. There is any amount of vesicular, scoriaceous, and amygdaloidal lava, all more or less altered, but for investigation it was desired to have a compact and, as far as might be, fresh lava, and at the same time to avoid material concerning which there might be some doubt as to its dike nature. For this purpose the basalt flow on the saddle between Highwood and Pinewood peaks was selected. It is by no means ideal material, as will be seen, but it is as good as the district affords, and serves a satisfactory purpose for the study of this effusive magma.

Megascopic characters.—In the hand specimen the rock has the ordinary gray-black compact basaltic appearance. Close inspection shows numerous small, dark, augite prisms as phenocrysts. The fracture is rough and hackly. In places small threads and irregular spots of a white substance are seen, indicating some secondary material deposited in it. It is mostly calcite.

Microscopic characters.—In thin section the rock is seen to consist of phenocrysts of augite, altered olivine, and leucite (and analcite) in a base consisting of a smaller generation of leucite, iron ore, and a greenish glass. The augite is of the usual greenish Highwood type, full of glass inclusions; it is fairly well crystallized, unaltered, and attains a length of 2 mm. The leucite shows the ordinary outlines of this mineral; it is entirely free from the usual inclusions and does not show the multiple twinning structure, due probably to its rather small size, as the crystals do not exceed 0.4 mm. in diameter. Its fractures are filled with calcite and a greenish material of a chloritic nature, substances which have wandered in from the groundmass. Where this greenish substance is present there is a feeble aggregate polarization between crossed nicols; elsewhere the mineral is completely isotropic. There are irregular and often elongated areas of a colorless, limpid, isotropic substance of low refractive index and distinct cubic cleavage; these are undoubtedly analcite. It is observed that some of the polygonal-shaped sections also have a cubic cleavage, and these may be leucites altered to analcite, but this seems doubtful. The chemical analysis and the microscopic study prove clearly that both of these minerals are present, but since neither shows any marked individuality, it is impossible to distinguish clearly between them.

Olivine is not a common mineral; it is not present as unchanged material, since it is completely altered to a black substance and recalls certain resorption pseudomorphs. It is readily recognized by the characteristic sections and rough cross cleavage; the cracks are filled with greenish chloritic substance.

The glassy groundmass is in part idiochromatic; in part colorless of itself, but it is completely filled with the greenish chloritic dust, which colors it pale green. It is also filled with the dots and rods of black iron ore so commonly seen in partially crystallized femic lavas. Under low power this combines into an aggregate which appears as a greenish-brown base.

Chemical composition.—An analysis of this type, by Doctor Foote, is given under I in the table on the next page.

The analysis shows the characteristics of the Highwood magmas, as may be seen by reference to II, one of the granular rocks of the stocks, and III, the same kind of magma in dike form; the latter, however, shows a different relation of the alkalies, a fact discussed under the description of that type. The type which in some other regions seems to bear the closest resemblance to this rock is a leucite-bearing effusive from Khoi, Persia, whose analysis has been previously quoted and is here repeated. For the sake of comparison, analyses of two other leucitic rocks are given, and it will be noted that they have a much higher ratio of soda to potash than the one under discussion. This is generally true, and in the present case is due to the considerable quantity of analcite present.

Analyses of phyro-shonkinose (leucite-basalt) and related rocks.

	I.	II.	III.	IV.	V.	VI.	VII.
SiO_2	47.98	49.59	47.82	49.65	46.51	46.06	0.798
Al_2O_3	13.34	14.51	13.56	14.39	11.86	10.01	.130
Fe_2O_3	4.09	3.51	4.73	4.21	7.59	3.17	.026
FeO	4.24	5.53	4.54	3.48	4.39	5.61	.058
MgO	7.01	6.17	7.49	6.27	4.73	14.74	.175
CaO	9.32	9.04	8.91	10.12	7.41	10.55	.166
Na_2O	3.51	3.52	4.37	3.21	2.39	1.31	.056
K_2O	5.00	5.60	3.23	5.46	8.71	5.14	.053
H_2O+	2.10	1.95	3.37	2.37	2.45	1.44	.113
H_2O-					1.10		
CO_2	1.24						
TiO_2	.58	.36	.67		.83	.73	.008
P_2O_5	1.03	.15	1.10	.79	.80	.21	.007
SO_3	Trace.	.02	Trace.		Trace.	.05	
Cl	.21	.13	.04		.04	.03	.006
CuO					Trace.		
NiO					.04		
MnO	Trace.	Trace.	Trace.	.25	.22	Trace.	
BaO	.50	.49	.16		.50	.32	
SrO	.14	.21	.21		.16	.20	
	100.29	100.78	100.20	•100.19	99.73	99.57	
Cl=O	.07	.03	.01		.01	.01	
Total	100.22	100.75	100.19		99.72	99.56	

I. Shonkinose (leucite-basalt) from saddle between Highwood and Pinewood peaks. H. W. Foote, analyst.

II. Leucite-shonkinose (leucite-shonkinite) from East Peak stock, Highwood Mountains. E. B. Hurlburt, analyst.

III. Monchiquose (analcite-basalt) from dike in Highwood Gap. H. W. Foote, analyst.

IV. Shonkinose (leucitophyre) from near Khoi, Persia. J. Steinecke, analyst. Zeit. Naturw. Halle, vol. 6, 1887, p. 12.

V. Chotose (leucitite) from Bearpaw Peak, Bearpaw Mountains, Montana. H. N. Stokes, analyst. Weed and Pirsson, Am. Jour. Sci., 4th series, vol. 2, 1896, p. 147.

VI. Missourote (missourite) from Shonkin stock, Shonkin Creek, Highwood Mountains. E. B. Hurlburt, analyst.

VII. Molecular proportions of No. 1.

Mineral composition or mode.—The mineral composition can not be determined with exactness because of the impossibility of distinguishing between small leucites and analcites, and in certain areas between these and the isotropic base. The latter is also specked with iron ore and other minerals in form too minute for measurement. Making due allowance for these things, the following table shows a measurement determination made with as careful estimations as possible:

Mode of shonkinose.

Minerals.	Units measure.	Volume, per cent.		Specific gravity.				Weight, per cent.
Iron ore	55	4.0	×	5.2	=	20.80	=	4.17
Apatite	19	1.3	×	3.2	=	4.16	=	1.57
Calcite	26	1.9	×	2.7	=	5.13	=	2.00
Olivine	122	9.0	×	3.4	=	30.60	=	11.81
Augite	225	16.5	×	3.3	=	54.45	=	20.98
Leucite	176	12.9	×	2.4	=	30.96	=	11.92
Analcite	129	9.5	×	2.2	=	20.90	=	8.07
Base	608	44.7	×	2.3	=	102.81	=	39.69
Total	1,360	99.8		---		269.81		100.21

The ratios of the femic minerals to one another and to the salic ones plus the base are the most nearly correct of this determination, which, on the whole, gives a fair idea of the relative quantities of the minerals present.

Classification in prevailing systems.—In these the rock is of course a leucite-basalt in which part of the leucite is replaced by analcite, which appears to be of secondary origin. It resembles very strikingly the leucite-basalts of the Bearpaw Mountains, described some years since by the writer. The fact that the olivine is not present as such by reason of its resorptive alteration does not change the classification and throw it into the leucitites; its chemical composition shows that it belongs in the former group.

Classification in the new system.—The position of this type in the new system is shown in the following calculation, which gives its norm and place:

Calculation of the norm of shonkinose.

	Analysis.	Molecular ratio.	Or.	Ab.	Ne.	An.	Di.	Ol.	Mt.	Il.	Ap.
SiO_2	47.98	0.798	318	66	90	42	244	38	----	----	----
Al_2O_3	13.34	.130	53	11	45	21	----	----	----	----	----
Fe_2O_3	4.09	.026	----	----	----	----	----	----	26	----	----
FeO	4.24	.058	----	----	----	----	15	9	26	8	----
MgO	7.01	.175	----	----	----	----	107	68	----	----	----
CaO	9.32	.166	----	----	----	21	122	----	----	----	23
Na_2O	3.51	.056	----	11	45	----	----	----	----	----	----
K_2O	5.00	.053	53	----	----	----	----	----	----	----	----
TiO_2	.58	.008	----	----	----	----	----	----	----	8	----
P_2O_5	1.03	.007	----	----	----	----	----	----	----	----	7
Cl_2	.21	.003	----	----	----	----	----	----	----	----	3
Rest	4.06	----	----	----	----	----	----	----	----	----	----
Total	100.29	----	53	11	45	21	122	38	26	8	7

Or	29.47	53.85
Ab	5.76	
An	5.84	
Ne	12.78	
Di	26.83	42.11
Ol	5.68	
Mt	6.03	
Il	1.22	
Ap	2.35	
Rest	4.06	
Total	100.02	

Class, $\frac{\text{Sal}}{\text{Fem}}=\frac{53.85}{42.11}=1.2=$III, salfemane.

Order, $\frac{\text{L}}{\text{F}}=\frac{12.78}{41.07}=0.31=$lendofelic$=6$, portugare.

Rang, $\frac{Na_2O'+K_2O'}{CaO'}=\frac{109}{21}=5.1=$domalkalic$=2$, monchiquase.

Subrang, $\frac{K_2O'}{Na_2O'}=\frac{53}{59}=0.9=$sodipotasic$=$shonkinose.

This shows that the rock is a shonkinose, as its chemical composition at once indicates. It is interesting to observe that the norm shows no leucite whatever, but in its place orthoclase associated with nephelite. This arises from the fact that leucite and analcite replace them in the mode, and water plays its rôle. These relations are easily seen in the following equation:

Orthoclase. Nephelite. Water. Leucite. Analcite.

$$K_2Al_2Si_6O_{16}+Na_2Al_2Si_2O_8+2H_2O=K_2Al_2Si_4O_{12}+Na_2Al_2Si_4O_{12}.2H_2O.$$

That is, as water vapor was present analcite was formed and reduced what otherwise would have been orthoclase to leucite. This relation has been previously discussed in the description of the shonkinose of East Peak, and its bearing on the primary origin of the analcite has been pointed out. In the present case, however, there is evidence which was lacking in that rock. In this rock the leucites have their own definite crystal form and are evidently primary. They did not crystallize as orthoclase, to be reduced later on; they are not pseudomorphs; they are original. But if they are original, is not the analcite original also? It is the same question as in the East Peak case.

The texture of the rock is porphyritic, and it is therefore a phyro-shonkinose.

CHAPTER VII.

GENERAL PETROLOGY OF THE HIGHWOOD REGION.

INTRODUCTION.

As a group the Highwood rocks show certain features which serve to bring them into a definite family and to distinguish them from rock groups of other regions. The fact that a complex of igneous rocks from a given region may possess what may be termed "clan" characters is now so well known to all petrographers that it is unnecessary to dwell upon the fact. Service to the science at present is best rendered by bringing to light so large a number of such clans that sufficient data may be obtained to enable petrologists to reduce this relation of igneous rocks to definite order and understanding.

In some groups this clan character is best expressed in the relations of the minerals to one another, or in the texture or production of a certain mineral or minerals through the series. In other cases it is best shown by chemical characters which persist through a number of magmas. In the Highwood rocks it is exhibited in part by the mineral and in part by the chemical composition. It is, of course, understood that the mineral pecularities are dependent on the chemical composition combined with the physical conditions under which the magmas cooled and crystallized. For this reason the general chemical character of the Highwood magmas will be considered first.

CHEMICAL CHARACTERS OF HIGHWOOD MAGMAS.

For consideration of this subject twenty analyses are available. They are given in the tables following. Of these analyses, VI is calculated from the microscopic mineral analysis, confirmed as previously shown by a partial chemical analysis; XIII is a partial analysis in which TiO_2 and P_2O_5 have been weighed with alumina; the rest are accurate modern chemical analyses, made according to the latest approved methods. By them practically every considerable rock mass and kind of rock in the district is represented.

Analyses of Highwood rocks.

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.
SiO_2	65.54	57.18	56.45	59.24	58.04	53.47	55.23	51.00	51.75	52.05
Al_2O_3	17.81	18.54	20.08	13.84	17.25	12.43	18.31	17.21	14.52	15.02
Fe_2O_3	.74	3.65	1.31	5.46	2.49	6.19	4.90	2.41	5.08	2.65
FeO	1.15	1.15	4.39	1.36	1.24	3.73	2.06	4.23	3.58	5.52
MgO	.98	.69	.63	4.79	1.79	3.07	1.85	6.19	4.55	5.39
CaO	1.92	2.31	2.14	5.60	3.50	7.23	3.63	9.15	7.04	8.14
Na_2O	5.55	4.48	5.61	3.13	3.37	3.40	4.02	2.88	2.93	3.17
K_2O	5.58	8.58	7.13	4.22	10.06	7.59	6.43	4.93	7.61	6.10
H_2O+	.54	2.10	1.51	2.02	1.95	-------	1.84	.63	2.25	.35
H_2O-	------	-------	.26	-------	-------	-------	-------	------	-------	------
CO_2	------	-------	-------	-------	-------	.40	-------	------	-------	------
TiO_2	.11	.30	.29	.22	.30	1.19	.42	.13	.23	.47
P_2O_5	Trace	.05	.13	.34	.22	.84	.58	.33	.18	.21
SO_3	------	.06	-------	.08	Trace.	.62	.23	.03	Trace.	.02
Cl	------	.77	.43	.04	Trace.	-------	.32	Trace	.05	.24
MnO	------	Trace.	.09	Trace.	Trace.	-------	Trace.	Trace	Trace.	Trace.
BaO	------	.49	-------	Trace.	-------	-------	.46	.34	.30	.42
SrO	------	Trace.	-------	-------	-------	-------	Trace.	.14	.07	.28
	99.92	100.35	100.45	100.34	100.21	100.16	100.28	99.60	100.14	100.03
O=Cl	------	.17	.10	.01	-------	-------	.08	------	.01	.06
Total	99.92	100.18	100.35	100.33	100.21	100.16	100.20	99.60	100.13	99.97

I. Pulaskose (syenite) from Highwood Peak. L. V. Pirsson and W. L. Mitchell, analysts. (712.)[a]

II. Pulaskose (tinguaite-porphyry) from dike at edge of Middle Peak stock. H. W. Foote, analyst. (746.)

III. Pulaskose (sodalite-syenite) from Square Butte. W. H. Melville, analyst. (767.)

IV. Adamellose (trachyandesite) from flow North Willow Creek. E. B. Hurlburt, analyst. (787.)

V. Highwoodose (tinguaite-porphyry) of Highwood type from great dike below Highwood Gap. E. B. Hurlburt, analyst. (724.)

VI. Highwoodose (nosean-syenite) from south side of Highwood Gap. Microscopically calculated, L. V. Pirsson, analyst. (683.)

VII. Monzonose (gauteite) from dike on upper Aspen Creek. H. W. Foote, analyst. (854.)

VIII. Shoshonose (monzonite) from Highwood Peak. E. B. Hurlburt, analyst. (715.)

IX. Fergusose (fergusite) from Arnoux stock at head of Shonkin Creek. E. B. Hurlburt, analyst. (827.)

X. Borolanose (basic syenite) from Middle Peak stock. E. B. Hurlburt, analyst. (739.)

[a] The numbers are those of the original collection.

Analyses of Highwood rocks.

	XI.	XII.	XIII.	XIV.	XV.	XVI.	XVII.	XVIII.	XIX.	XX.
SiO_2	51.94	50.11	50.00	47.88	49.59	47.98	46.73	47.82	46.04	46.06
Al_2O_3	15.78	17.13	19.36	12.10	14.51	13.34	10.05	13.56	12.23	10.01
Fe_2O_3	4.07	3.73	3.87	3.53	3.51	4.09	3.53	4.73	3.86	3.17
FeO	3.17	3.28	2.67	4.80	5.53	4.24	8.20	4.54	4.60	5.61
MgO	3.48	2.47	2.18	8.64	6.17	7.01	9.27	7.49	10.38	14.74
CaO	6.04	5.09	4.96	9.35	9.04	9.32	13.22	8.91	8.97	10.55
Na_2O	3.44	3.72	3.63	2.94	3.52	3.51	1.81	4.37	2.42	1.31
K_2O	7.69	7.47	8.52	5.61	5.60	5.00	3.76	3.23	5.77	5.14
H_2O+	2.17	4.47	3.53	1.52	1.95	2.10	1.24	3.37	2.87	1.44
H_2O-	------	------	.46	.70	------	------	------	------	------	------
CO_2	------	------	------	.12	------	1.24	------	------	------	------
TiO_2	.39	.82	(a)	.77	.36	.58	.78	.67	.64	.73
P_2O_5	.59	.67	(a)	1.11	.15	1.03	1.51	1.10	1.14	.21
SO_3	.29	.08	------	None.	.02	Trace.	------	Trace.	Trace	.05
Cl	.08	.07	------	Trace	.13	.21	.18	.04	.11	.03
Cr_2O_3	------	------	------	.03	------	------	------	------	------	------
NiO	------	------	------	Trace	------	------	------	------	------	------
MnO	Trace	Trace.	------	.15	Trace.	Trace.	.28	Trace.	Trace	Trace.
BaO	.42	.63	------	.46	.49	.50	(?)	.16	.48	.32
SrO	.28	.35	------	.13	.21	.14	(?)	.21	.25	.20
	99.83	100.09	99.18	99.99	100.78	100.29	100.56	100.20	99.76	99.57
O=Cl	.02	.02	------	------	.03	.05	.04	.01	.03	.01
Total	99.81	100.07	99.18	99.99	100.75	100.24	100.52	100.19	99.73	99.56

a In Al_2O_3.

XI. Borolanose (syenite-porphyry) from dike at edge of Shonkin stock. W. M. Bradley, analyst. (832.)

XII. Borolanose (basic syenite) from Palisade Butte. H. W. Foote, analyst. (772.)

XIII. Borolanose (basic syenite) from Shonkin Sag laccolith. W. F. Hillebrand, analyst (partial anal.) (1006.)

XIV. Montanose (shonkinite) from Shonkin Sag laccolith. W. F. Hillebrand, analyst (including ZrO_2=0.03; F=0.05; S=0.03; Cr_2O_3=0.03; V_2O_3=0.04). (1004.)

XV. Leucite-shonkinose (leucite-shonkinite) from East Peak stock. E. B. Hurlburt, analyst. (760.)

XVI. Shonkinose (leucite-basalt) from flow on saddle between Highwood and Pinewood peaks. H. W. Foote, analyst. (799.)

XVII. Shonkinose (shonkinite) from Square Butte. L. V. Pirsson, analyst. (765.)

XVIII. Monchiquose (analcite-basalt) from dike on east side Highwood Gap. H. W. Foote, analyst. (687.)

XIX. Biotite-cascadose (Highwood minette) from dike on Arrow Peak. H. W. Foote, analyst. (736.)

XX. Missourote (albanose) or missourite from Shonkin stock, head of Shonkin Creek. E. B. Hurlburt, analyst. (824.)

A study of these analyses shows at once that the magmas are generally low in silica, which ranges from 65 to 46 per cent, but in the majority of types is about 50 per cent. Alumina is present in about average amount, and runs from 20 to 10 per cent. With diminishing silica and alumina the lime, iron, and magnesia rise. The most interesting and important relations are to be seen in the alkalies. There is some variation in the ratios of soda to potash, but in general the potash predominates. In some cases, especially in the siliceous and in the most femic or basic magmas, this predominance of potash is marked. It is to be noted also that high alkalies occur with high lime—for example, in one case K_2O 7.5, Na_2O 3.0, and CaO 7.0 per cent, respectively. This combination, the alkalic character with high lime and potash, is the distinctive feature of the Highwood magmas, which runs through the whole family and gives it a distinctive petrographic stamp.

That this is an uncommon feature in rock magmas is clearly seen in Washington's tables of analyses, where perpotassic and dopotassic rocks are rare. In speaking of this, Washington remarks[a] that of the whole number of analyses the perpotassic and dopotassic taken together form only 5.1 per cent, the perpotassic only 0.5 per cent. The Highwood analyses contribute a considerable proportion of these magmas. Outside of the central Montana province the only regions in which rocks so high in potash are found, so far as the writer knows, is in Italy and in the Leucite Hills of Wyoming.

In the table of analyses there is one exception, XVIII, the monchiquose dike, in which soda predominates. This may have been caused by a secondary enrichment in soda.

The parent magma of the Highwoods—the source from which these types sprung—must have possessed the same general characters as the types themselves. It was thus of a very definite nature and its probable composition will be discussed in a later portion of this chapter.

[a] Prof. Paper U. S. Geol. Survey No. 14, p. 104.

NORMS OF HIGHWOOD ROCKS.

The chemical character of the rocks is, of course, seen also in the following tables of their calculated norms. The order in which these norms are given is the same as in the preceding table of analyses. On examining this table the feature that first attracts attention is the general dominance of orthoclase over albite—a dominance that increases toward the femic end of the series, and at this end there is only one marked exception. Toward this end also as the silica falls the orthoclase is eventually replaced by leucite. These facts show the strongly potassic nature of these magmas. Like the increase in nephelite, augite, olivine, and apatite toward the femic end, they are the result of expressing in mineral form the series of chemical analyses previously given, and show, of course, similar distinctive features. The manner in which the iron ores range through the group with small variations in percentage is also an interesting feature.

Taken as a whole the series shows also how gradually rocks merge into one another chemically and mineralogically, and how arbitrary must be lines of distinction based on these properties. The group affords also in several ways an excellent illustration of the new system of classification. These features are much more clearly seen by comparing the norms than by comparing the analyses. Thus the first three are of pulaskose; alkali feldspars are the chief components; small quantities of other minerals occur, but play very subordinate rôles. In adamellose alkali feldspars are the most important, but are associated with considerable quantities of quartz, anorthite, and diopside. In highwoodose alkali feldspars with some diopside are again the chief minerals, all the rest being in subordinate amounts, and the notable feature is the very great preponderance of orthoclase over albite. In monzonose the albite and orthoclase are equal, and the notable increase in anorthite is the chief feature. In shoshonose the series is becoming distinctly more femic, the alkali feldspars are balanced by an equal amount of anorthite and diopside, while nephelite and olivine are not insignificant. Next comes fergusose, a new type of remarkable texture, consisting of orthoclase, nephelite, and diopside; the great preponderance of the orthoclase is, as in highwoodose, the distinctive feature, and one that separates it from the norms of rocks formerly classed as nephelite-syenites, since the latter contain quantities of soda which expresses itself in large amounts of nephelite, albite, or both.

Calculated norms of Highwood rocks.

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.
Orthoclase	32.7	50.6	42.3	24.5	59.5	45.0	37.8	28.9	45.0	36.1
Albite	46.7	25.2	28.3	26.2	14.7	13.1	31.4	10.0	3.7	7.3
Anorthite	7.0	6.7	9.7	11.1	3.1	------	12.8	19.5	3.9	9.2
Quartz	7.3	------	------	10.2	------	1.4	------	------	------	------
Leucite	------	------	------	------	------	------	------	------	------	------
Nephelite	------	------	3.4	------	1.7	------	1.4	8.0	11.4	7.4
Sodalite	------	5.8	6.0	------	4.9	------	------	------	------	2.9
Noselite	------	------	------	------	------	5.7	------	------	------	------
Diopside	2.0	3.7	------	11.4	9.7	17.4	1.1	19.4	23.75	24.5
Olivine	------	------	5.9	------	------	------	------	8.3	1.5	6.2
Hypersthene	2.7	------	------	6.7	------	------	4.1	------	------	------
Wollastonite	------	------	------	------	.4	1.9	------	------	------	------
Magnetite	1.2	2.8	1.9	3.6	3.0	7.7	5.6	3.5	7.4	3.9
Ilmenite	.2	.6	.6	.5	.6	2.3	.8	.2	.5	.9
Hematite	------	1.8	------	2.9	.3	------	1.1	------	------	------
Apatite	------	------	.3	.7	.3	2.0	1.3	.7	.3	.3
Acmite	------	------	------	------	------	2.8	------	------	------	------
Hyalophane	------	------	------	------	------	------	------	------	------	------

I. Pulaskose from Highwood Peak.
II. Pulaskose from dike at Middle Peak.
III. Pulaskose from Square Butte.
IV. Adamellose from flow on North Willow Creek.
V. Highwoodose from dike north of Highwood Gap.
VI. Highwoodose from south of Highwood Gap.
VII. Monzonose from dike on upper Aspen Creek.
VIII. Shoshonose from Highwood Peak.
IX. Fergusose from Arnoux stock, Shonkin Creek.
X. Borolanose from Middle Peak stock.

Calculated norms of Highwood rocks.

	XI.	XII.	XIII.	XIV.	XV.	XVI.	XVII.	XVIII.	XIX.	XX.
Orthoclase	45.0	44.5	49.5	33.4	33.4	29.5	22.2	18.9	23.9	1.1
Albite	9.4	9.4	------	------	.5	5.8	1.6	17.8	------	------
Anorthite	6.1	8.1	8.9	3.3	7.8	5.8	8.3	7.8	5.8	5.3
Quartz	------	------	------	------	------	------	------	------	------	------
Leucite	------	------	.9	------	------	------	------	------	8.3	22.7
Nephelite	6.0	11.1	16.8	13.4	13.4	12.8	6.3	9.7	8.8	5.9
Sodalite	1.0	------	------	------	1.9	------	1.0	------	1.9	------
Noselite	2.8	.7	------	------	------	------	------	.5	------	------
Diopside	16.7	10.2	10.8	28.4	29.1	26.8	37.9	23.4	25.0	36.7
Olivine	1.8	2.2	.8	9.1	5.7	5.7	11.4	7.9	13.0	18.6
Hypersthene	------	------	------	------	------	------	------	------	------	------
Wollastonite	------	------	------	------	------	------	------	------	------	------
Magnetite	5.8	5.3	5.6	5.1	5.1	6.0	5.1	7.0	5.6	4.6
Ilmenite	.7	1.5	.9	1.5	.8	1.2	1.5	1.2	1.2	1.4
Hematite	------	------	------	------	------	------	------	------	------	------
Apatite	1.0	1.7	.7	2.7	.3	2.4	3.7	2.6	2.7	.3
Acmite	------	------	------	------	------	------	------	------	------	------
Hyalophane	------	------	------	------	------	------	------	------	------	1.4

XI. Borolanose from dike, Shonkin stock.
XII. Borolanose from Palisade Butte.
XIII. Borolanose from Shonkin Sag laccolith.
XIV. Montanose from Shonkin Sag laccolith.
XV. Shonkinose from East Peak stock.
XVI. Shonkinose from flow, Pinewood Peak saddle.
XVII. Shonkinose from Square Butte.
XVIII. Monchiquose from dike, Highwood Gap.
XIX. Cascadose from dike, Arrow Peak.
XX. Missourote (albanose) from Shonkin stock.

This is followed by borolanose, of which there are four examples, X to XIII; orthoclase is still the chief ingredient, but there is a considerable increase in the soda minerals, albite and nephelite, and also in anorthite. In montanose there is a great increase in augite and olivine, but there is only 3 per cent of anorthite. The rock is thus composed of alkalic feldspars and lenads, potash strongly dominating, with ferromagnesian minerals; it is peralkalic. This lesser amount of anorthite distinguishes montanose from the next type, shonkinose, which contains enough anorthite to carry it over the line into the domalkalic rang—monchiquase, but, as the norms show, the montanose and shonkinose are very close together. In XVIII, the exceptional type of the region, the preponderance of the sodic minerals carries the rock into the dosodic subrang monchiquose and differentiates it from shonkinose. In the next norm, that of cascadose, the large proportion of lenad minerals, as compared with feldspar, carries us into a different order, the lenfelic one under salfemane, kamerunare; leucite begins to appear, and this finds an important position in albanose (missourote). The latter, it will be remembered, on account of the predominance of augite and olivine, stands on the very border line of the next class, dofemane.

GEOLOGIC OCCURRENCE OF THE DIFFERENT MAGMAS.

The geologic occurrence of the magmas is by no means the same as the geologic occurrence of the rocks, for the rocks are the result of not only the chemical properties but the physical environment of the magma. Thus, as is well known, the same magma in different modes of occurrence produces rocks which differ in minerals and texture. This is illustrated in a general way in the Highwoods. Thus, for instance, the intrusive stock of East Peak, the dike of Highwood minette (cascadose) of Arrow Peak, and the basaltic effusive (shonkinose) of Pinewood Peak saddle are from practically the same magma, with slight variations, as may be seen in the following comparison:

Comparison of rocks different in geologic occurrence but similar in chemical composition.

	East Peak stock.	Arrow Peak dike.	Pinewood Peak flow.
SiO_2	49.6	46.1	48.0
Al_2O_3	14.5	12.2	13.3
Fe_2O_3	3.5	3.7	4.1
FeO	5.5	4.6	4.2
MgO	6.2	10.3	7.0
CaO	9.0	9.0	9.3
Na_2O	3.5	2.4	3.5
K_2O	5.6	5.8	5.0

The intrusive rock (fergusite) of the Arnoux stock and the dike (syenite-porphyry or borolanose) at the edge of the Shonkin stock have practically the same magma.

Comparison of chemical composition of stock and dike.

	Stock.	Dike.
SiO_2	51.8	51.9
Al_2O_3	14.5	15.8
Fe_2O_3	5.1	4.1
FeO	3.6	3.2
MgO	4.6	3.5
CaO	7.0	6.0
Na_2O	2.9	3.4
K_2O	7.6	7.7

Other instances might be adduced, but these are sufficient to show that there is no peculiar relation in this area between the chemical composition of the magmas and their geologic mode of occurrence. Whatever be their origin below, the same material has been forced upward into both the stocks and the dikes and has appeared in effusive form on the surface. The dikes therefore do not appear to be diaschistic in the sense of Brögger[a]—that is, they are not complementary; they are rather aschistic. It appears to the writer, however, that the stocks themselves show diaschistic features and that in the sense of Brögger both stocks and dikes, and the laccoliths as well, belong to the same category and represent "laccolithic differentiation." This is treated later in this work.

It may then be stated that in the Highwoods neither the dikes nor the flows represent any more highly differentiated forms of magmas than do the stocks which they accompany. Special cases may be selected in which types on the one hand more salic, and on the other more femic, than some particular stock would appear, but this does not affect the general truth of the statement. On the contrary, the most highly differentiated types which the district affords—the pulaskose (syenite) of Highwood Peak and the albanose (missourite) of the Shonkin stock—are both granular rocks occurring in the stocks themselves.

STOCKS AND LACCOLITHS.

Without discussing at this point the general question of the origin of igneous rocks, it may be pointed out that the occurrence of two distinct types, such as the syenite (pulaskose) and monzonite (shoshonose) of Highwood Peak in the canal of such an evident volcanic

[a] Grorudit-Tinguait-Serie, 1894, p. 153.

center can not fail to be of great interest. In the same way the occurrence of shonkinite with kernels of syenite in the laccoliths has an important bearing on the question of differentiation in igneous magmas, a bearing which has already been discussed by various authors. The general advance which has been made in solving problems of this character during the last ten years has led the writer to modify in some degree his earlier views in regard to the laccoliths in the Highwoods. These modifications have been in part given under the geologic description of Square Butte and will be mentioned in the following discussions.

RELATIVE VOLUMES OF THE DIFFERENT MAGMAS.

In a general way the magmas may be roughly divided into two main groups—salic and femic, or acid and basic, or basaltic and trachytic, to give a choice of terms. The areal mapping and field study shows that in this area the amount of the salic magmas compared with the femic is small. This is seen in a variety of ways. It is shown by the dikes, as it is safe to say that for one salic dike there are twenty femic of the same size. It is also seen in the effusive materials—the flows and breccias—the total volume of the femic far exceeding that of the salic, in spite of the fact that the latter, being overlain by the femic, have been saved from erosion, while the femic have in considerable volume disappeared. The same fact is shown in the stocks, the volume of Highwood syenite being smaller than the monzonite, yet it is one of the largest masses of salic rock in the district. The other stocks do not show any strictly salic types, being salfemic in composition. But the most striking evidence is found in the laccoliths, which are worth some attention, as they afford interesting data in this connection which may be used in several directions and in the elucidation of their structure.

SHONKIN SAG LACCOLITH.

If it is assumed that this laccolith is a short section of a cylinder with a diameter of a mile and an average height of 150 feet, it contains very nearly 3,000,000,000 cubic feet of rock. If it is assumed that the mass of augite-syenite (borolanose) which forms the kernel has a diameter of 2,000 feet and an average thickness of 50 feet, it would have a volume somewhat over 150,000,000 cubic feet, in round numbers; that is, the syenite constitutes about one-twentieth of the whole mass. These figures are, of course, approximate (see p. 47). They can not, however, be very far from the truth, and for the purpose they are just as valuable as if they were exact. The point is that there is in the laccolith about 19 times as much shonkinite (montanose) as syenite (borolanose). The bearing of these proportions will be brought out in a later paragraph.

SQUARE BUTTE.

By reference to the cross section of this laccolith given on page 54 it will be seen that it can not be considered as having an exactly cylindrical shape. A considerable portion of the shonkinite has been lost by erosion, but if it is assumed that the laccolith has the form and cross section given, the relative volumes generated by such figures of revolution around a common vertical axis may be computed. This has been kindly done for me by Prof. J. Barrell, who obtained the volume by multiplying the area on one side of the axis by the distance passed over by its center of gravity in the revolution about the axis, both analytic and graphic methods being used as checks. The result of this is as follows:

	Cubic mile.
Total volume of the laccolith	0.69
Inner volume of syenite	.13
Outer volume of shonkinite	.56

That is to say, the syenite comprises 18.8 per cent of the laccolith and the shonkinite 81.2 per cent, thus showing, as previously stated, that the femic magmas are in large excess.

PALISADE BUTTE.

At Palisade Butte there is no such sharp line of demarcation between the light and dark portions. Moreover, the amount of erosion has been so great that the laccolith can not be restored beyond imagining that it had a form similar to that of Square Butte. Enough remains, however, to show clearly that the volume of the dark shonkinite is (and was) much greater than that of the lighter-colored rock.

DIFFERENTIATION IN LACCOLITHS.

From the proportions just given in the case of Square Butte and the Shonkin Sag laccolith some interesting and important relations may be deduced. If one believes that these three laccoliths, with their varied and peculiar structures, present good examples of the results of differentiation, it would be also natural to think, since they stand close together in a group, that they had been formed from a common magma and in toto should be similar in composition. Since the chemical composition of the parts and their relative volumes are known the composition of the original magma is easily computed, with the results given in the next table.

Computation of original magmas of laccoliths.

	I.	II.	III.	IV.	V.	VI.
SiO_2	50.0	47.9	48.0	56.5	46.7	48.5
Al_2O_3	19.4	12.1	12.4	20.1	10.1	12.0
Fe_2O_3	3.9	3.5	3.5	1.3	3.5	3.0
FeO	2.7	4.8	4.7	4.4	8.2	7.4
MgO	2.2	8.6	8.3	0.6	9.7	7.8
CaO	5.0	9.4	9.2	2.1	13.2	11.1
Na_2O	3.6	3.0	3.0	5.6	1.8	2.5
K_2O	8.5	5.6	5.8	7.1	3.8	4.4

I. Syenite (borolanose) from Shonkin Sag laccolith.
II. Shonkinite (montanose) from Shonkin Sag laccolith.
III. Mixture, 1 part syenite and 19 parts shonkinite, of I and II.
IV. Syenite (pulaskose) from Square Butte.
V. Shonkinite (shonkinose) from Square Butte.
VI. Mixture, 13 parts syenite and 56 shonkinite, of IV and V.

When one considers that the relative volumes are approximations and that the composition of small pieces is held to represent the composition of large masses, it must be confessed that III and VI are very much alike; they represent the same magma and differ mostly in ferrous iron and lime—a result which is due to the fact that the specimen from which analysis V was made probably contains rather more augite than the average of the whole mass.

It is clear, then, that the laccoliths could have been formed by the intrusion of bodies of a shonkinitic magma from a source below, which furnished a uniform material, and that the syenite masses in that case must have been produced by the local interior concentration of a very small part of the feldspathic elements of these magmas.

So far as the writer can see, the arrangement of the varied parts in the laccoliths could have occurred only in one of three ways: First, there might have been by some process an injection of shonkinite, and afterward one of syenite into its center. Against this the mechanical difficulties seem insurmountable; there is no explanation of the lack of contact phenomena between the two kinds of rock; it is difficult to understand why the process occurred in two laccoliths while in the third there should be a gradual transition from shonkinite to syenite, and why separate upward movements of syenite magma should occur in this region only in the centers of the laccoliths. In view of these facts this theory may be confidently dismissed.

OSMOTIC THEORY.

The structure[a] of the laccoliths has been explained by the assumption that the magma was really of a syenite character, and that by

[a] Johnston-Lavis, H. J., Highwood Mountains of Montana and magmatic differentiation, a criticism: Brit. Assn. Adv. Sci., Rept. Liverpool Meeting, 1896, p. 792.

absorption of sedimentary material it became changed to shonkinite—lime, iron, and magnesia being the oxides absorbed. This is the osmotic theory. The writer has already pointed out[a] that this view is untenable for several reasons. There are no sediments in this region which have the proper composition to effect such a change, which must have taken place after the intrusion. There is nothing wanting in the sediments, and one can plainly see in the Shonkin Sag laccolith that the beds have simply been lifted and that nothing has been absorbed. Moreover, the intrusion has occurred in sandstones, not in calcareous, magnesian, iron-bearing beds. In addition, it is not a question of a narrow basic mantle, for, as just pointed out, the greater part of these masses consists of shonkinitic magma, and therefore, in the case of Square Butte, for example, the amount of material absorbed would have to be sufficient to reduce the 12.8 per cent alkalies of the syenitic rock to the 5.6 per cent of the shonkinitic, or to increase the magnesia from 0.6 to 9.7 for four-fifths of the entire mass. This would require the melting up and absorption of an incredible amount of country rock when one considers the amount of magma. Again, one may pertinently ask, If this occurred in the laccoliths why did it not occur at Highwood Peak, where the syenitic rock is found in direct contact with similar sediments without any basic border intervening? Whatever may be the merits of the osmotic theory in explaining the phenomena seen in other regions—and in regard to them the writer offers no opinion—it is certain that in the localities in Montana studied by him, at Castle Mountain, at Yogo Peak, and in the Highwoods, where basic outer rock mantles occur, the hypothesis has not a leg to stand upon, and it would never be offered by any petrographer who had studied the occurrences in these districts.

The facts disclosed compel us to fall back upon the third method of explanation—that the laccoliths have been formed in the place where they now are by processes which took place in a body of magma that was originally homogeneous.

THEORIES OF DIFFERENTIATION.

The term differentiation has been consistently used by the writer for a number of years to express the idea that different rocks are formed from a parent body of homogeneous magma without reference to the processes which have caused this result. This is considered to be demonstrated through the repeated observations of a great number of careful and competent students of petrologic phenomena. In the opinion of the author this term should be used in a geologic sense, as in a geologic way it has been demonstrated. Many theories have been advanced in explanation of this process along the lines of physical chemistry, but no one of them has been admitted by all to be a competent cause in every case. This in no

[a] Shonkin Sag laccolith: Am. Jour. Sci., 4th series, vol. 12, 1901, p. 13.

wise invalidates the actuality of the process. The geologist has pointed out the fact; it remains for the physical chemist to explain it if he can. Nothing is to be gained by denying it.

The many discussions of this subject which have been presented by workers in petrology are so well known that the writer has no intention of giving them in résumé in this place; the more important ones have been recently well summed up in a paper by Schweig[a] on the differentiation of igneous magmas, who adds an important suggestion of his own, which will be considered later. The theories may be classified into three groups—those which depend on the force of crystallization, those depending on some other form of molecular flow, and those which appeal to some force whose methods of operation are unknown, such as electricity.

Becker[b] has shown that pure molecular flow or diffusion is an agency acting with extreme slowness, and therefore as an explanation for such relatively small bodies of magma as the Highwood laccoliths intruded into the upper crust and cooling with relative rapidity, the writer is not inclined to regard it as competent or probable. Its rapidity, however, supposing that it can take place, must depend in large measure on the fluidity of the magma, and this is of necessity more or less unknown. It must not be forgotten, however, that so long as crystallization is able to take place the viscosity of a magma is never too great to prevent molecular flow, since it is through this that the molecules are able to arrange themselves in crystal form. The molecular oxides may not move over a great distance, but they are able to move.

Schweig[c] has offered the important suggestion that differentiation may be caused by the crystallizing out of definite minerals through fall of temperature or increase of pressure and the separation of such crystals from the mother liquor through specific gravity. If this takes place under high pressure, then by the removal of such pressure the crystals would become melted again and furnish chemically different magmas.

It seems rather difficult to accept this view in the simple form thus stated, as experience does not seem to show that there is the settling out of crystals through a greater specific gravity as postulated. Nothing is more common than to observe great vertical thicknesses of igneous rocks exposed by erosion, often for several thousand feet, and find that they are of uniform character throughout from top to bottom. This the author has seen repeatedly, and many instances will occur, no doubt, to all petrographers. Indeed, the author has never seen any instance where a direct proof of such settling could be observed, though a few are claimed in the literature. On the other

[a] Differentiation der Magmen: Neues Jahrb. für Min., Beil. Bd. 17, 1903, p. 516.
[b] Some queries on rock differentiation: Am. Jour. Sci., 4th series, vol. 3, 1897, p. 21.
[c] Loc. cit., p. 563.

hand, a priori it would seem to be a very natural result, and where it does not happen its failure must be attributed to the viscosity of the mother liquor in which the crystals are formed. Yet it is evident that the mother liquor can not be so viscous as to prevent molecular flow, otherwise crystallization could not take place. These are perplexing questions, and our knowledge of the physical properties of molten magmas is as yet far too incomplete to enable us to answer them with certainty.

It must be admitted, however, that the cross sections of the Highwood laccoliths furnish some evidence that specific gravity has been a factor in their formation, for the bottom portions are composed, as has been shown, of a relatively great thickness of heavy femic rock, upon which rests a much less thickness of lighter salic rock, and then in the Shonkin Sag laccolith, the only one whose upper part is still uneroded, is a very small thickness of the femic type again. It would be interesting to know in this connection whether the association of syenitic and shonkinoid intrusive rock masses, described by Merrill,[a] if seen in better exposures or more thoroughly studied, would show the femic rock below as well as above the salic type, and thus conform to the Highwood occurrences. More complete study and description would give a better idea of what seems to be a most interesting occurrence of differentiation in place.

DIFFERENTIATION PRODUCED BY CRYSTALLIZATION.

In recent years rock masses which show differentiation in place have received great attention from petrographers, and justly so, since they furnish the most precise indications yet obtained concerning the nature of the processes that have caused differentiation. Especially is this true of those processes which show different border zones, such as the Highwood laccoliths. The tendency at present appears to be to view them as caused by some process of crystallization, and in this connection Washington[b] has pointed out that we should expect that rock type which appears in the largest amount to be the one formed at the border. This is on the principle that in the case of a solvent and solute it is the solvent that crystallizes out first, an idea which, as applied to crystallization in molten magmas, we owe to Lagorio.[c] Washington further suggests that the differentiated border zones would be found in laccoliths of medium composition, monzonitic and foyaitic, while in extreme types, such as are granitic on the one hand and gabbroid on the other, with the solvent in very great excess the small amount of solute would be mechanically caught and crystallized with it or forced inward and solidified as a small core at the center of the mass.

[a] Notes on some eruptive rocks from Montana: Proc. U. S. Nat. Mus., vol. 17, 1895, pp. 643, 665. Conf., also, Bull. U. S. Geol. Survey No. 110, 1893, p. 43.

[b] Igneous complex of Magnet Cove: Bull. Geol. Soc. America, vol. 11, 1900, p. 409.

[c] Tschermaks Min. Mitt., vol. 8, 1887, p. 513.

This conception of Washington's with respect to the femic ("gabbroid") type is perfectly realized in the Shonkin Sag laccolith.

Washington, however, attributes the whole process to the force of crystallization, and does not deem convection currents to be at all essential.[a] He says: "It would go on by collecting along the rough borders in accordance with the well-known tendency of crystallizing bodies to grow about sharp nuclei, the solute molecules being mechanically pushed aside toward the center."

With this view, which is a clear exposition of the idea, also expressed by others, that the force of crystallization is alone competent to produce differentiated border zones, the writer can not agree, because, as it seems to him, there is a misconception involved in it, for a series of very small units is made to do duty as one very large unit. Let us suppose that we have a mass of mobile magma a mile in diameter and that the moment has arrived in the process of cooling when some compound can crystallize out. This begins at the outer border, as stated, and not at the center. Now, in the center are oxide molecules, which are to be moved to the outer border, a distance of half a mile. It can scarcely be thought that the force of crystallization can act through an intervening distance of such magnitude with a pull sufficient to attract the central molecules to the outer border, for crystallization acts only through relatively short distances. It is of no aid to the solution of the problem to think that at any intervening distance the molecules would come together and form another crystal, for the moment that has happened the forces of crystallization would, so to speak, come to rest and cease to operate. The crystal, then, at the intervening distance is, so far as the forces within its radius of action are concerned, a dead body, and we must find some force other than that of crystallization to transport it to the outer border. Unless the pull is felt from border to center it is difficult to see how crystallization can operate. It might also be imagined that the force does not operate directly upon the central molecule, but indirectly through the intervening ones, these being linked together, by their tendency to crystallize, like a train of cars. The train as a whole would then move in the direction of the molecules at either end, upon which a stronger force operates, and in this case the locomotive that moves it are those molecules at its outer end, which, being within the crystallizing influence of the outer border, are irresistibly drawn forward to the solidifying crystal. Then come the next in the train, and so on.

The objection to this method of explanation is that, if the attraction between the mineral molecules were strong enough to act as a link in the train, they would crystallize and the continuity of the train would be broken. We should have to imagine the whole mass in a state of absolute equilibrium, each molecule attracted equally in all directions by

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[a] Loc. cit., p. 410.

its fellows, the whole being drawn without a break in the continuity of events toward the outer border. Should there be a break anywhere in the equilibrium, the molecules would fly together and crystallize in that spot, which would set up a new center of attraction as powerful as any spot at the outer edge, and the molecules would, over large areas, move thither, and this of course would disturb the equilibrium elsewhere; thus the whole mass would go on crystallizing without reference to the outer border. In fact, if we appeal to crystallization alone in this way, convection currents are not only no aid but they can not be present, since they would tend to disturb equilibrium, and there must be no disturbance of any kind. Thus it appears to the writer that the mere statement of the conditions necessary for this view are sufficient to refute it. It seems that if we consider crystallization alone as the operating force, in the ultimate analysis it resolves itself into the force acting from border to center, and when one considers the magnitude of the distance and the frictional resistance in the magma, which in any case can never be perfectly mobile, but must possess a certain amount of viscosity, it does not appear possible to appeal to this alone as a competent agent to produce such results. Accepting crystallization alone, it would also be difficult to explain why the lower layer of femic rock is so very thick and the upper one so very thin.

ELECTRICITY.

Some writers have suggested that electric currents may play some function in the process of differentiation. But as yet we know so little in regard to the electric properties of molten magmas, beyond the fact that they appear to be similar to aqueous salt solutions,[a] that nothing of value can be advanced in this direction. When electricity is suggested as a possible agent the thought of the German proverb comes irresistibly to mind:

> "Was man sich nicht erklären kann
> Das sieht man als elektrisch an."

COMBINED EFFECT OF CONVECTION AND CRYSTALLIZATION.

In the original paper on Square Butte the writer placed great stress on molecular diffusion, and was inclined to believe that crystallization had played no part in determining its differentiation, the fact that different femic minerals were found in the two rock varieties leading to this conclusion. In the light of recent work, and especially of Becker's proof of the slowness of molecular diffusion, this view should now be modified, and it is thought that a combination of convection currents and the tendency to crystallize first at the outer walls of the laccolithic chamber may possibly be sufficient causes. It seems

[a] Barus and Iddings, Electrical conductivity in rock magmas: Am. Jour. Sci., 3d series, vol. 44, 1892, p. 242.

almost impossible to resist the view that in an inclosed mass of magma sufficiently mobile for local differentiation to take place convection currents due to unequal cooling would occur. On the upper surface and along the outer walls cooling would take place more rapidly; on the floor of the chamber, protected by the heated mass above and with heated rocks below, less rapidly. Thus there would be a tendency along the top and sides for the magma to grow heavier and to descend. Material from the more highly heated central part would tend to rise and replace this, and thus currents would be established in the magma, rising in the center, flowing off to the sides at the top, and descending along the cooler walls. This process is illustrated by the familiar experiment of showing the convection currents in a vessel of boiling water with sawdust. Such currents, once established, would continue as long as sufficient mobility remained in the magma to permit them.

At some period crystallization would take place, and this most naturally would begin at the outer walls. It would not begin at the top because the material would arrive there from below at its highest temperature. Moving off toward the sides the material begins to cool and descend and becomes coolest as it nears the floor; here crystallization would commence. The first substance to crystallize is the solvent, which in this case would be the femic minerals, chiefly augite. Part of the material solidified would remain attached to the outer wall and form a gradually increasing crust, and part would be in the form of free crystals swimming in the liquid and carried on in the current. Probably at first, as the liquid moved inward over the floor of the laccolith and became reheated, these crystals would remelt, giving rise to numerous small spots of magma of a different composition, which would slowly diffuse. As time went on, however, there would be a constantly increasing tendency for the crystals to endure; they would be carried greater and greater distances. But as they are solid objects and of greater specific gravity than the liquid, there might be a tendency for the crystals to drag behind and accumulate on the floor of the chamber. Moreover, from the heat set free at the time of their crystallization and from the resulting concentration of the chemically combined water vapor in the magma, the residual liquid would tend to have its mobility kept undiminished, since these would be factors which would tend to counteract the increase in viscosity due to cooling. In this manner it may be possible to understand how there would form a femic marginal crust and a great thickness of the femic material at the bottom of the laccolith. As the cooling went on the edges of the outer crust would rise more and more toward the top, finally spreading over it, and as a result the crust should be thinner on the top than elsewhere, as in the Shonkin Sag laccolith, in which the upper crust of femic rock is still preserved.

If, notwithstanding the evidence previously mentioned, there is a tendency for the crystals, on account of their greater specific gravity, to overcome viscous resistance and sink through the fluid, this might greatly aid in the process just described. And it is also possible to imagine that if the crystals melted there might be, in spite of diffusive tendencies, a retardation in some degree of the spots of more femic magma thus formed and their local accumulation.

In this way the solute—in this case the oxides which form feldspars—might gradually accumulate toward the center and eventually solidify there. The process might go on until a definite eutetic solution resulted, when crystallization might produce a rock very different from that which had been forming. This would explain the case of the salic rock of Square Butte, for the resulting inner mass contained such a proportion of the femic elements, water, vapor, etc., that these combined to form hornblende instead of augite. In the Shonkin Sag laccolith the water vapors appear to have largely concentrated along the inner walls of the outer femic crust, producing, when the inner mass solidified, a mantle with pegmatitic development. Although the erosive dissection at Palisade Butte is much greater than at the other two laccoliths, the remaining portions would seem to indicate that the process went on much more rapidly, and consequently the separation into parts was much less pronounced. The explanation just offered is based, with modifications, essentially on the suggestion of Becker[a] as to the process by which differentiation can occur in laccoliths through a combination of crystallization and convection currents.

The hypothesis tentatively offered above seems to explain those, the most common, cases of laccolithic differentiation in which the outer shell is of femic type; it does not so well explain those with a salic outer shell. Washington[b] has suggested that in those magmas of preponderant salic character the salic molecules compose the solvent, and as this crystallizes first it produces the salic mantle. The only difficulty in this view is that it would then be necessary to show that in the rock mass composing the salic mantle the salic minerals have crystallized first, and are therefore automorphic against the femic ones, thus proving that the latter crystallized last. The writer does not know of any evidence concerning this point in the literature, and has never had the opportunity of studying a distinct laccolith with salic border, the only case where the mass was more salic at the margin, coming under his observation, being the Blackhawk intrusive stock in the Castle Mountains.[c] In this case the mass was not an inclosed body of magma such as would be formed in a laccolith, and

[a] Fractional crystallization of rocks: Am. Jour. Sci., 4th series, vol. 4, 1897, p. 257.
[b] Loc. cit., p. 410.
[c] Weed and Pirsson, Geology of the Castle Mountain mining district: Bull. U. S. Geol. Survey No. 139, 1896, p. 89.

it passes from a granular rock at the center to a porphyry at the outer edge, and the process appears to have been otherwise than in the Highwood laccoliths.

DIFFERENTIATION IN THE STOCKS.

The process of differentiation suggested above for the laccoliths could not apply to the stocks which form eruptive centers, at least not without modification of the process. This is perhaps the best illustrated at Highwood Peak. Here we find the same association of salic and femic types seen in the laccoliths, but while the two taken together form a single mass intruded in the sediments, there is no such orderly arrangement of parts, and the two kinds have a sharp contact against each other, the pulaskose being the later, since it holds angular fragments of the monzonoid rock. There have been, therefore, two successive upthrusts of magma, the second after the former had solidified; and the differentiation has not occurred in the place where the masses now are, but at some lower level; and it also could not have been by the separation of a solid from a liquid by the simple process suggested above in the laccoliths, since both were intruded in liquid form.

The suggestion that a differentiated stock might be explained by laccolithic differentiation below, followed by a later upward movement of the mass, has been already made by the writer in the case of Yogo Peak, in the Little Belt Mountains of Montana,[a] and this idea has been recently extended by Prof. F. D. Adams to explain the varied rock types and their arrangement at Mount Johnson, in the Province of Quebec,[b] where syenite (laurvikose) is found associated with essexite (essexose). In this case, however, the rock varieties grade into each other; there is not a sharp contact between them, showing that the upward movement took place before any solidification occurred and involved both alike. This might have been the case at Yogo Peak, but could not have been at Highwood Peak, as mentioned above.

From this center of eruption there have been in all four upthrusts of magma, two of them shown by extrusive flows, two in the stock itself. They have occurred in the order and with the compositions shown in the subjoined table:

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[a] Petrography of the igneous rocks of the Little Belt Mountains, Montana: Twentieth Ann. Rept. U. S. Geol. Survey, pt. 3, 1900, p. 566.

[b] The Monteregian Hills: Jour. Geol., vol. 11, 1903, p. 281.

Composition of Highwood Peak magmas.

	I.	II.	III.	IV.
SiO_2	59.2	48.0	51.0	65.5
Al_2O_3	13.8	13.3	17.2	17.8
Fe_2O_3	5.5	4.1	2.4	.7
FeO	1.4	4.2	4.2	1.1
MgO	4.5	7.0	6.2	1.0
CaO	5.6	9.3	9.1	.9
Na_2O	3.1	3.5	2.9	5.5
K_2O	4.2	5.6	4.9	5.6

I. Adamellose (trachyandesite) flow from North Willow Creek.
II. Shonkinose (analcite-basalt) from Pinewood saddle.
III. Shoshonose (monzonite) from Highwood Peak.
IV. Pulaskose (syenite) from Highwood Peak.

This is based on the view that the stocks are of later age than the extrusives surrounding them. At East Peak, for example, this is clearly the case, for the two, as described elsewhere, are seen in contact, the stock cutting upward through the effusives. They are not seen in such clear contact at Highwood Peak, and yet the arrangement, as may be seen on the map, is such as to lead to this conclusion, which is, moreover, the general one in such cases.

Repeated attempts have been made to discover whether in the above series of analyses any mathematical relations are present which would throw light on the processes of differentiation or would serve to connect them with the other magmas of the area. These attempts have not been so completely successful as could be wished. The great difficulty in the way of such work is that we have no exact knowledge of the relative volumes of magmas involved. Some general facts are, however, clear. Thus, if we should suppose that II has differentiated out of I, we can see that there is much less silica, the same alumina, a large increase in ferrous iron, lime, and magnesia, and a small increase in alkalies, especially potash. If it were true that II represents a differentiated product of I, then there should be a complementary magma to correspond. Using various proportions of I and II, attempts have been made to calculate this magma and see if it would be shown by III, IV, or some other analyzed magma of the district, but without much definite success. The study that has been made leads to the conclusion that all four represent differentiated products, and if they have developed from a parent magma then m I+n II=a and m III+n IV=b, while m'a+n'b= original magma, and none of these have been found and analyzed. We do not know the relative volumes, as we did in the laccoliths, and can not therefore assign values to m, n, m′, and n′ and discover the exact composition of the original magma or of its first cleavage products.

It is of interest to note, however, that if we assume the simplest case, that the volumes of all four are equal—that is, if we take their simple averages, we obtain these results:

Averages and comparison of analyses.

	A.	B.	C.	D.	E.
SiO_2	53.6	58.2	55.9	52.9	52.1
Al_2O_3	13.5	17.5	15.0	15.6	15.0
Fe_2O_3	4.8	1.6	3.2	3.0	2.7
FeO	2.8	2.6	2.7	4.8	5.5
MgO	5.8	3.6	4.7	5.2	5.4
CaO	7.4	5.0	6.2	8.2	8.1
Na_2O	3.3	4.2	3.7	3.2	3.1
K_2O	4.9	5.3	5.1	4.9	6.1

A. Average of I and II from Highwood Peak center.
B. Average of III and IV from Highwood Peak center.
C. Average of I, II, III, and IV from Highwood Peak center.
D. Average of monzonite analyses (Petrography Little Belt Mountains, Twentieth Ann. Rept. U. S. Geol. Survey, pt. 3, 1900, p. 478).
E. Borolanose (basic syenite) from Middle Peak stock Highwood Mountains.

The examination of the average of these analyses will show that it is that of a typical monzonitic magma. In D there is given for comparison the average of a number of analyses of monzonites used in the description of the rocks of Yogo Peak. It has a very close resemblance to this. It is also of interest to observe that, while neither it nor I nor II is exactly like any Highwood magma, they have a general resemblance to many of them; for example, C and E are much alike. In this connection it should be recalled that the Middle Peak stock is much older, as shown elsewhere, than any of the products of igneous activity belonging to the Highwood Peak center, and that, with the exception of possessing a border facies, which differs from the main mass chiefly in a textural manner and either not at all or but very slightly in a chemical way, it is entirely undifferentiated. It is therefore probable that it represents the original magma from which I, II, III, and IV have differentiated, and it is possible that by combining them in the proper proportions this composition could be more exactly realized. The other stocks of the area are of the same category as that at Middle Peak, and the further discussion of the origin of all these is deferred until that of the dikes has been taken up.

COMPOSITION OF THE ORIGINAL MAGMA.

Before dismissing the stock rocks it is of interest to surmise yet further what might have been the composition of the original magma from which they were all derived. It is understood that this can, of course, only be done by averaging those of them of which we have analyses. For this purpose there are available analyses of the Middle Peak, East Peak, and Arnoux stocks. To use the Highwood stock, we must obtain some average of its two rock types. The monzonitic rock is, however, in excess over the syenitic, how much is not known, but certainly more than twice as much is present. To be on the safe side, we will assume it is twice as much, not more. If this is added and the average of all four taken, we shall have the result given in column A of the following table. In column B is given the analysis of the Middle Peak stock, which, as previously mentioned, is much the oldest in the district, and therefore probably the least differentiated. Considering how rough such an approximation must be the agreement is really very close. It seems probable, then, that the original magma from which all these rocks were derived had approximately the composition shown in column A.

Average and comparison of analyses.

	A.	B.
SiO_2	52.2	52.0
Al_2O_3	15.3	15.0
Fe_2O_3	3.3	2.7
FeO	4.4	5.5
MgO	5.2	5.4
CaO	7.8	8.1
Na_2O	3.3	3.2
K_2O	6.1	6.1

DIFFERENTIATION AND DERIVATION OF DIKES.

Just as in the preceding section it has been shown that a lack of definite knowledge of the relative volumes of the magmas prevents us from obtaining exact results by combining them, so the same difficulty arises in trying to determine the origin and derivation of the dikes. In spite of this, however, some general relations may be shown which are interesting and instructive. For instance, the dikes in and around Highwood Gap are clearly referable to either salic or femic types, and taken together they are complementary, so that it seems probable that if combined in proper proportions they would indicate the parent magma from which they were derived. For this purpose there are four analyses, two of salic and two of femic types, as shown by I, II, III, and IV in the subjoined table of analyses. In the next four columns, V, VI, VII, and VIII, are shown the averages obtained by combining each salic and femic magma in equal proportions.

Combination and comparison of analyses of dikes and stocks.

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.
SiO_2	58.0	57.2	46.0	47.8	52.0	51.1	52.9	52.5	52.0	51.8	52.2
Al_2O_3	17.3	18.5	12.2	13.6	14.7	15.3	15.4	15.5	15.0	14.5	15.3
Fe_2O_3	2.5	3.6	3.9	4.7	3.2	3.7	3.6	4.2	2.7	5.1	3.3
FeO	1.2	1.2	4.6	4.5	2.9	2.9	2.9	2.9	5.5	3.6	4.4
MgO	1.8	0.7	10.4	7.5	6.1	5.5	4.7	4.1	5.4	4.6	5.2
CaO	3.5	2.3	9.0	8.9	6.3	5.6	6.2	5.6	8.1	7.0	7.8
Na_2O	3.4	4.5	2.4	4.4	2.9	3.4	3.9	4.5	3.2	2.9	3.3
K_2O	10.1	8.6	5.8	3.2	7.9	7.2	6.7	5.9	6.1	7.6	6.1

I. Highwoodose (tinguaite-porphyry) from dike at Highwood Gap.
II. Pulaskose (tinguaite-porphyry) from dike at Middle Peak. South Peak ridge.
III. Cascadose (Highwood minette) from dike at Arrow Peak.
IV. Monchiquose (analcite-basalt) from dike at Highwood Gap.
V. Average of I and III.
VI. Average of II and III.
VII. Average of I and IV.
VIII. Average of II and IV.
IX. Borolanose (basic syenite) from dike at Middle Peak stock.
X. Fergusose (fergusite) from dike at Arnoux stock, Shonkin Creek.
XI. Average of four stocks.

In IX and X are analyses of two of the stocks and in IX the average of four of them, which has been obtained as explained on a previous page. The close general similarity of the averages obtained by this simplest of all methods among themselves and with the stocks and their average must convince every unprejudiced reader that it has been perfectly possible for the varied dikes to originate by the splitting up of the magmas represented in the stocks. It is also evident that it has been done in the main by the concentration of lime, iron, and magnesia in one portion of the original magma and a consequent enrichment in silica, alumina, and alkalies in another. The main differences between the stocks and the dike averages are in the relations of lime and ferrous and ferric irons. If we consider only total iron, disregarding the state of oxidation, the differences mostly disappear. In lime, however, the differences are over 1 per cent, but this is the only striking disagreement to be observed.

It will be noted that this presupposes that the volume of material of which the salic dikes are composed is equal in amount to that of which the femic dikes are formed, and it was pointed out at the beginning of this chapter that in actual volume as they appear at the surface the salic dikes are very greatly outclassed by the femic ones. If we accept the view that the complementary dikes have been formed by the dissociative differentiation of a magma in composition similar to that of the Middle Peak stock, the unavoidable inference would be that the femic by-product had appeared at higher horizons in dike form much more largely than the salic, and that the greater part of the latter had solidified at lower levels as intrusive masses, to be, perhaps, exposed by later and deeper erosion. If this is so, it would be only in keeping with what the writer has previously pointed out as the rule in such cases.[a]

On the other hand, the salic dikes could have formed from a much more femic magma than that indicated above, just as the salic cores of the laccoliths have, though not necessarily by exactly the same processes, and this would, of course, have left much larger volumes of femic material to form dikes. Either this supposition or the one mentioned above is a perfectly reasonable one, and the evidence at hand is not sufficient to decide definitely between them.

GENERAL DIFFERENTIATION OF IGNEOUS ROCKS.

In a relatively small body of inclosed magma, such as we find in the laccoliths, it is not difficult to imagine a process by which differentiation has taken place and an outer femic mantle produced by crystallization aided by other agencies, such as convection currents. This involves the separation of a solid from a liquid, and evidently the differentiation in stocks, such as Highwood Peak and the complementary dikes where both varieties have been injected in liquid form, could not be explained in this way, at least not without modification. Still less could we explain thus the variation of the mass of one stock from the mass of another if we believe that they have been formed from some greater, deeper body of magma that was once homogeneous.

Schweig has suggested, as previously mentioned, that under sufficient pressure compounds might be forced to crystallize out, and that then, descending, through greater specific gravity, heterogeneity would be produced. If the pressure should then be relieved, they would be incapable of existing in solid form, would melt, and liquid masses of differing composition might thus be formed. In some ways this is a very tempting hypothesis. For instance, as has been shown, there occurred at Highwood Peak an eruption of salic lava (adamellose, trachyandesite) filled with more or less resorbed hornblende, and this was followed by femic lava (shonkinose, analcite-leucite-basalt) in which augite completely replaces hornblende. We could imagine that in the lava column under great pressure hornblende was forced to crystallize, especially as under such a condition the water vapor necessary for its formation, but not for augite, would be present.

[a] Am. Jour. Sci., vol. 50, 1895, p. 116.

These hornblendes, descending, through gravity, would enrich the lower portion of the column in lime, iron, and magnesia. When eruption then took place a salic lava would be ejected, and the pressure being removed the remaining hornblendes which had not yet had time to descend would start to remelt, but would not have time enough before the mass chilled and prevented complete refusion. Hence we find them partially resorbed. This would be followed by a femic magma, but the water having mostly escaped and the pressure been relieved with the establishment of the opening of the conduit to the surface, this lava would have iron ore, olivine, and augite in the place of hornblende, which had had opportunity to completely remelt.

So far the hypothesis is tenable, but in the following events we are confronted by the fact that at Highwood Peak, in the next eruption, that of the monzonitic rock of the stock, there is a less femic magma, which was succeeded by one the most salic in the whole district—a quartz-bearing pulaskose. Evidently some entirely new arrangement in the mechanism of movement and eruption must be devised to meet this. The same difficulty arises in the case of some of the dikes, whose order of succession is given in a later paragraph.

And again, if we accept what appears to be the field evidence at Middle Peak, the differentiated dikes made their appearance earlier than the stock whose composition they unitedly represent.

These will serve as fair examples, which might be almost indefinitely increased from other districts, of the difficulties that stand in the way of a complete acceptance of this theory. To them should be added, as already pointed out, the homogeneous character of masses exposed by erosion through great vertical distances. In fairness, however, it should be admitted that these difficulties are just as pertinent to many other explanations which have been offered for the differentiation of molten magmas as they are for this one.

As time goes on it becomes more evident that the problem is an increasingly complex one; no single explanation of one occurrence will do for all. In what we call the differentiation of rock magmas many factors have worked together; in one place one factor or set of factors has been dominant, in other places these are less so. For a single occurrence a satisfactory explanation may be offered, but a general one must take a comprehensive view of the whole field, of the varied phenomena to be explained, and of the difficulties which arise. There are varied agencies to be considered—crystallization, convection currents, molecular diffusion under varied aspects, tendency to form eutectic mixtures, addition and subtraction of water vapor, increase and decrease of heat, increase and relief of pressure, the mechanism of the movements of magma produced by crustal displacements, the effects of these upon the relative saturation of the magmas with certain compounds, the effects of varied electrical status, and many others.

The truth of the matter is that we are as yet not at all prepared to give a general explanation of the differentiation of magmas. There are many things to be learned before we can do so. Every suggestion which has as much merit as that of Schweig's helps, but can not be accepted for the whole truth. It appears to the writer that at the present time a statement of the problem presented by some of the phenomena and of the difficulties to be met would be most useful and would perhaps tend to prevent the development of obviously wrong hypotheses. Further discussion of this subject here would transcend the proper limits of this work, and the writer hopes to take it up at another time and place.

MATHEMATICAL RELATIONS OF MAGMAS SHOWN BY GRAPHIC METHODS.

In the discussion of the origin of the rocks of the Little Belt Mountains the author showed [a] that their molecular ratios, as given by the analyses, could be arranged in a simple linear series forming a diagram from which, if the percentage of one oxide of an element in a rock in the district was known, its entire chemical composition could be deduced. Washington [b] has extended the same process to the complex at Magnet Cove, Arkansas. With the Highwood analyses the attempt to form a similar simple linear series has not succeeded, and it is evident that they are more complex or that the requisite data are not at hand. In addition to the relations which have been previously given in this discussion others might be shown; thus, if we should take one part of the syenitic rock of the Square Butte laccolith and combine it with one part of the shonkinoid portion of the same mass (see III and XVII of the table of Highwood analyses previously given), we should obtain the result presented in column A below, which may be compared with the analysis of the Middle Peak stock, given in column B. The general resemblance is very close.

Comparison of analyses.

	A.	B.
SiO_2	51.5	52.0
Al_2O_3	15.0	15.0
Fe_2O_3	2.4	2.6
FeO	6.3	5.5
MgO	5.1	5.4
CaO	7.6	8.1
Na_2O	3.7	3.2
K_2O	5.4	6.1

[a] Twentieth Ann. Rept. U. S. Geol. Survey, pt. 3, 1900, p. 569.
[b] Foyaite-ijolite series of Magnet Cove: Jour. Geol., vol. 9, 1901, p. 645.

Although such relations are to be seen, the attempt to combine them and to place the whole group in mathematical relation has so far not succeeded, possibly because there is no definite relation, but in the belief of the writer it is because there is in this series no such initial starting point as was afforded by the analyses of the differentiated mass of Yogo Peak.

ARRANGEMENT OF VOLCANIC CENTERS.

There is no particular plan in the arrangement of the volcanic centers in the Highwoods; they show no such disposition as would enable one to say that they are placed on fault lines. It is evident that there is no profound faulting or tectonic disturbance to be seen in the Highwood area; the facts at hand are quite to the contrary. The general plan of the mountains and their geologic history already given show that the first upward movements of the magmas began with intrusion of laccoliths and of one stock. There is no evidence that this was attended by surface outbreaks, though this may have been the case. These movements were attended with shattering of the strata and the intrusion of dikes, and it was through this mass of weakened strata that the later outbursts took place, with intrusions of stocks now here now there. The outbreaks at the Shonkin center were of great violence and attended with profound effects upon the circumjacent beds, as is clearly shown by the remarkable aureole of radiant dikes that surround it, though it is possible that these were initiated near the stock in part by the contraction due to later loss of heat. The volcanic centers then appear to be caused by local outbreaks, the reason for the original selection of this locality not being evident.

There is at the present time with some geologists a tendency to deny that volcanic centers of eruption are determined by fault lines and fissures. It is true that in many regions they do not show any direct evidence of this, and the facts appear to indicate that they may occur quite independent of such lines, but it seems to the writer that it is not necessary to suppose they have been formed only after one method. The great amount of direct evidence at hand proves that they are sometimes located upon fault lines and sometimes they have been started by explosive chimneys blown through the crust, such as the Maaren of the Eifel district. In this case they do not have a definite arrangement of ground plan.

The Castle Mountain volcano to the south seems an example in this part of Montana of the relation between volcanoes and fault lines.[a]

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[a] Weed and Pirsson, Geology of the Castle Mountain mining district: Bull. U. S. Geol. Survey No. 139, 1896.

AGE AND ORDER OF SUCCESSION OF THE IGNEOUS ROCKS.

The absolute geologic age of the period of volcanic activity in the Highwood group can not be any more nearly told than that the products break through or are piled upon the Montana formation of the Cretaceous system, which are the youngest stratified rocks of the region. The outbreaks, however, may date from a somewhat later period than the close of the Montana, for the eastern laccoliths, which are probably the oldest igneous rocks, lie in the Montana itself, and the form and granular character of the masses indicate that these intrusions took place at considerable depths below the surface. There may then have been upon them beds younger than the Montana, which have since been carried away by erosion, but there is no direct evidence of this. It is evident, from the fact that the fragmental volcanic material lies in places practically upon the same beds as those which form the floor of the laccoliths, that a long period of erosion must have separated the intrusion of the latter from the outpouring of the former. How long this period was we have no means of judging, but one thing is certain, that the general geologic relations of the district and the character of its rocks indicate that its igneous activities are to be referred to a single geologic time phase. It is to be noted also that no beds of later age than the Montana are to be seen under the edges of the eroded cover of volcanic débris. From all of these circumstances it may be inferred that the time of igneous activity in the Highwoods was coincident with that of the general geologic disturbances at the close of the Cretaceous and in the early Tertiary, which have so profoundly affected the general Rocky Mountain region.

The order of succession of the igneous rocks has, in part, been previously mentioned. The geologic facts at our command show clearly distinct periods in the order of succession of the upward movement of the molten magmas, as follows: First, intrusion of the laccoliths, followed by very considerable erosion; second, outbreaks of volcanic activity yielding feldspathic lavas, followed by some erosion; third, intrusion of the stocks into the masses of feldspathic and basaltic extrusives.

Connected with these main episodes are a number of minor ones which deserve consideration on account of their bearing on the petrologic history of the region. The stock at Middle Peak, on the ridge between Highwood and South peaks, must be much older than the other stocks and antedate the outbreaks of extrusive material. This seems clear from the position of the sedimentary beds in the ridge, which are horizontal and in undisturbed position right up to the contact of the intrusion. It is impossible to imagine that the intrusion could have occurred along the crest of a narrow ridge composed of horizontal beds, displacing one half of the ridge and yet not disturbing the short, narrow strips of strata left in the other half. A great amount of erosion has occurred, by which the stock has been exposed to depths yielding moderately coarse granular rock and the surrounding strata carried away, the most resistant portion, the contact edge of metamorphosed sediments, standing up as a ridge. Far below this ridge, down in the valleys, as at Comb Butte as well as upon it, lie extrusive materials, and into these extrusives the other stocks are thrust. Hence the intrusion of Middle Peak, like that of the laccoliths, antedates by a considerable period of erosion the volcanic outbreaks, as stated above.

The ridge, however, as shown on the map, is cut transversely by a great number of dikes, of both feldspathic and basaltic types. These have also aided in the metamorphism and general stiffening of the structure and in resistance to erosion. They run directly to the contact edge of the stock and then cease. For this reason they clearly appear to be cut off by it and to be older than it is. While the exposures of the stock on the western slopes of the ridge are much broken down and largely of slide rock, this general fact seems evident. The evidence in the field then shows that there was here, first, an intrusion of various dikes, then that of the stock cutting them off, then a period of erosion, and then volcanic outbreaks. The field evidence in regard to the dikes is, on the other hand, opposed by a certain petrographic fact—exactly the same types of rocks found in the dikes are also found elsewhere in the area in other dikes cutting the breccias and therefore of much later date. This is especially notable, for example, in those basaltic types full of large biotite phenocrysts (Highwood minettes), called in the new classification "phyro-biotitic shonkinose." One of these occurs on the Middle Peak ridge and also cutting the extrusives of Lava Peak. It is, of course, in nowise impossible that this should occur, yet at the same time it is surprising to find such a peculiar and distinctive type of rock produced at two different periods separated by a long interval of time. The field evidence, however, is so much the stronger that we must accept this as a fact, if the previous interpretation is correct. That it is is also indicated by the recurrence of certain peculiar leucitic types in the laccoliths and again later in and around the Shonkin core.

In regard to the relative age of the feldspathic and basaltic dikes in the Middle Peak ridge, the only evidence was found on the slopes leading down to Highwood Gap, where the basaltic type was found in one case clearly cutting the feldspathic.

In regard to the later system of dikes, all that can be said is that the basaltic ones cut the basaltic flows and breccias and that the feldspathic ones cutting the Shonkin stock are, so far as we have evidence, the latest rocks of the region.

Summing up, then, all the evidence at hand as previously given, we have as the full order of succession of the igneous rocks:

1		Intrusions of laccoliths (salfemic magmas splitting into dosalic and salfemic).
	a	Intrusion of dikes, feldspathic (dosalic).
	b	Intrusion of dikes, basaltic (salfemic).
	c	Intrusion of Middle Peak stock (dosalic).
2		Erosion interval, followed by Highwood volcano.
3	*a*	Outbreak of feldspathic (dosalic) lavas.
	b	Outbreak of basaltic (salfemic) lavas.
	c	Intrusion of Highwood monzonite (dosalic).
	d	Intrusion of Highwood syenite (persalic).
4		Short erosion interval, followed by Shonkin volcano.
5	*a*	Outbreak of basaltic (salfemic) lavas.
	b	Intrusion of stocks, Shonkin, East, and Arnoux (salfemic).
	c	Intrusion of dikes, basaltic (salfemic).
	d	Intrusion of dikes, feldspathic (dosalic and persalic?).

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PUBLICATIONS OF UNITED STATES GEOLOGICAL SURVEY.

[Bulletin No. 237.]

The serial publications of the United States Geological Survey consist of (1) Annual Reports, (2) Monographs, (3) Professional Papers, (4) Bulletins, (5) Mineral Resources, (6) Water-Supply and Irrigation Papers, (7) Topographic Atlas of United States—folios and separate sheets thereof, (8) Geologic Atlas of the United States—folios thereof. The classes numbered 2, 7, and 8 are sold at cost of publication; the others are distributed free. A circular giving complete lists may be had on application.

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IOLA QUADRANGLE, KANSAS

BY

GEORGE I. ADAMS, ERASMUS HAWORTH, AND W. R. CRANE

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ERRATA.

[Bull. U. S. Geol. Survey No. 238.]

The work of Mr. F. C. Schrader in the adjacent Independence and Parsons quadrangles during the season of 1904 shows that certain mis-correlations were made in the survey of the Iola quadrangle. The necessary corrections have been made on the maps (Pls. I and II), and the data for correcting the text and Pls. III and IV are given below:

Pl. III, *for* Drum *read* Dennis.
for Cherryvale *read* Galesburg.
for Dennis *read* Mound Valley.
for Galesburg *read* Ladore.
Pl. IV, *for* Drum *read* Dennis.
for Dennis *read* Mound Valley.
Page 3, line 20, *for* Galesburg *read* Ladore.
line 21, *for* Dennis *read* Mound Valley.
line 22, *for* Cherryvale *read* Galesburg.
line 23, *for* Drum *read* Dennis.
Page 18, paragraph 1, line 10, *for* Galesburg *read* Ladore.
line 11, *for* Dennis *read* Mound Valley.
for Cherryvale *read* Galesburg.
for Drum *read* Dennis.
paragraph 4, line 1, *for* Galesburg *read* Ladore.
paragraph 5, line 1, *for* Dennis *read* Mound Valley.
paragraph 6, line 1, *for* Cherryvale *read* Galesburg.
Page 19, paragraph 1, line 1, *for* Drum *read* Dennis.
line 7, *for* Drum *read* Dennis.
paragraph 2, line 3, *for* Drum *read* Dennis.
line 4, *for* Dennis *read* Mound Valley.
line 5, *for* Galesburg *read* Ladore.
for Cherryvale *read* Galesburg.
paragraph 3, line 2, *for* Drum *read* Dennis.
Page 21, paragraph 5, line 5, *for* Galesburg *read* Ladore.
for Dennis *read* Mound Valley.
for Cherryvale *read* Galesburg.
for Drum *read* Dennis.
Page 22, line 17, *for* Drum *read* Dennis.
line 18, *for* Cherryvale *read* Galesburg.
line 19, *for* Dennis *read* Mound Valley.
line 20, *for* Galesburg *read* Ladore.
Page 75, paragraph 2, line 3, *for* Shaw *read* Dennis.
Page 79, line 14 from bottom, *for* Dennis *read* Mound Valley.
for Drum *read* Dennis.

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ILLUSTRATIONS

LETTER OF TRANSMITTAL.

Department of the Interior,
United States Geological Survey,
Washington, D. C., May 17, 1904.

Sir: I have the honor to transmit herewith the manuscript of a report on the economic geology of the Iola quadrangle, Kansas, by George I. Adams, Erasmus Haworth, and W. R. Crane, and respectfully recommend that it be published as a bulletin.

The report contains detailed information concerning the geology of a rapidly developing oil and gas field, and is intended to furnish information, chiefly of an economic character, in advance of the publication of the Iola folio.

Very respectfully,

C. W. Hayes,
Geologist in Charge of Geology.

Hon. Charles D. Walcott,
Director United States Geological Survey.

ECONOMIC GEOLOGY OF THE IOLA QUADRANGLE, KANSAS.

By George I. Adams, Erasmus Haworth, and W. R. Crane.

INTRODUCTION.

By George I. Adams.

LOCATION OF AREA DESCRIBED.

The Iola quadrangle is a rectangular area situated in southeastern Kansas (see fig. 1), its eastern and southern limits lying respectively 20 and 35 miles from the borders of the State. It is bounded by meridians 95° and 95° 30′ west longitude, and 37° 30′ and 38° north latitude. It has an area of about 944 square miles and includes nearly all of Allen County, the north half of Neosho County, the west border of Bourbon County, and the northwest corner of Crawford County. The larger towns in the quadrangle are Iola and Chanute, the growth of which has recently been stimulated by the finding of oil and gas. Humboldt, which is situated between Chanute and Iola, and Laharpe and Gas, which lie to the east of Iola and are connected with it by an electric line, are also in the more productive belt of the oil and gas territory. The towns of Erie, Shaw, Savonburg, Elsmore, Bronson, and Moran are at approximately the eastern limit of the field.

Although the Iola quadrangle is one of the arbitrary units employed for the purpose of mapping, its limits are fortunately situated with respect to the northern portion of the oil and gas field. It is purposed to continue the study of the oil and gas resources in this region, and for that reason the Independence quadrangle, which corners the Iola on the southwest, has already been surveyed topographically, and its geology is being studied. Those who are interested in oil and gas areas that do not fall within the Iola quadrangle may perhaps still be aided by this bulletin to a better understanding of the field in general, since the structure and general relations of the oil and gas are very similar in all parts of the Kansas-Indian Territory field as at present developed.

GENERAL STATEMENT.

The field work upon which this report is based was done in August and early September, in 1903, the general supervision of the work being in charge of the writer. It was divided into three portions: Prof. Erasmus Haworth, of Kansas University, collected and collated the information for the portion relating to the economic development; Prof. W. R. Crane, of Kansas University, made observations upon the pressure and flow of gas, his conclusions in regard to the

FIG. 1.—Sketch map showing location of Iola quadrangle (Pl. I) and area shown in Pl. II.

cause of the flow and the volume and approximate life of the wells in the field being presented in a separate chapter by him; and the writer, assisted by Mr. Millard K. Shaler, mapped the geologic formations and studied their structure and underground relations.

The Kansas oil and gas field has already been made the subject of several reports. The geology of this part of the State has been discussed by the university geological survey in volumes prepared under the direction of Professor Haworth, who has also written articles from time to time setting forth the available information pertaining to the economic development of the oil and gas resources of the State. In Bulletin 184[a] of the United States Geological Survey the writer gave an account of the general geologic relations and economic development of the Kansas-Indian Territory field up to the summer of 1901. Although the rapid progress made in exploiting oil and gas has changed the area and importance of the producing localities, the data obtained through the drilling of numerous wells have verified the general statements and conclusions of that report, so that it is still of interest as a general discussion of the field as a whole. That being the case, this bulletin will be confined to the consideration of the Iola quadrangle.

The university geological survey of Kansas, under the direction of Professor Haworth, had a number of students in the field doing geologic mapping during the summer of 1903. As a result of their work and through the courtesy of that survey there is presented in this report a more detailed mapping of the Fort Scott quadrangle (see Pl. II and fig. 1), which lies directly east of the Iola quadrangle, than would otherwise be available. This is valuable in discussing the underground relations of the formations, since the rocks that are encountered in the lower portions of the wells outcrop to the east, beyond the limit of the Iola quadrangle.

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[a] Adams, Geo. I., Oil and gas fields of the western interior and northern Texas coal measures and of the upper Cretaceous and Tertiary of the western Gulf coast: Bull. U. S. Geol. Survey No. 184, 1901.

GEOLOGY OF THE IOLA QUADRANGLE.

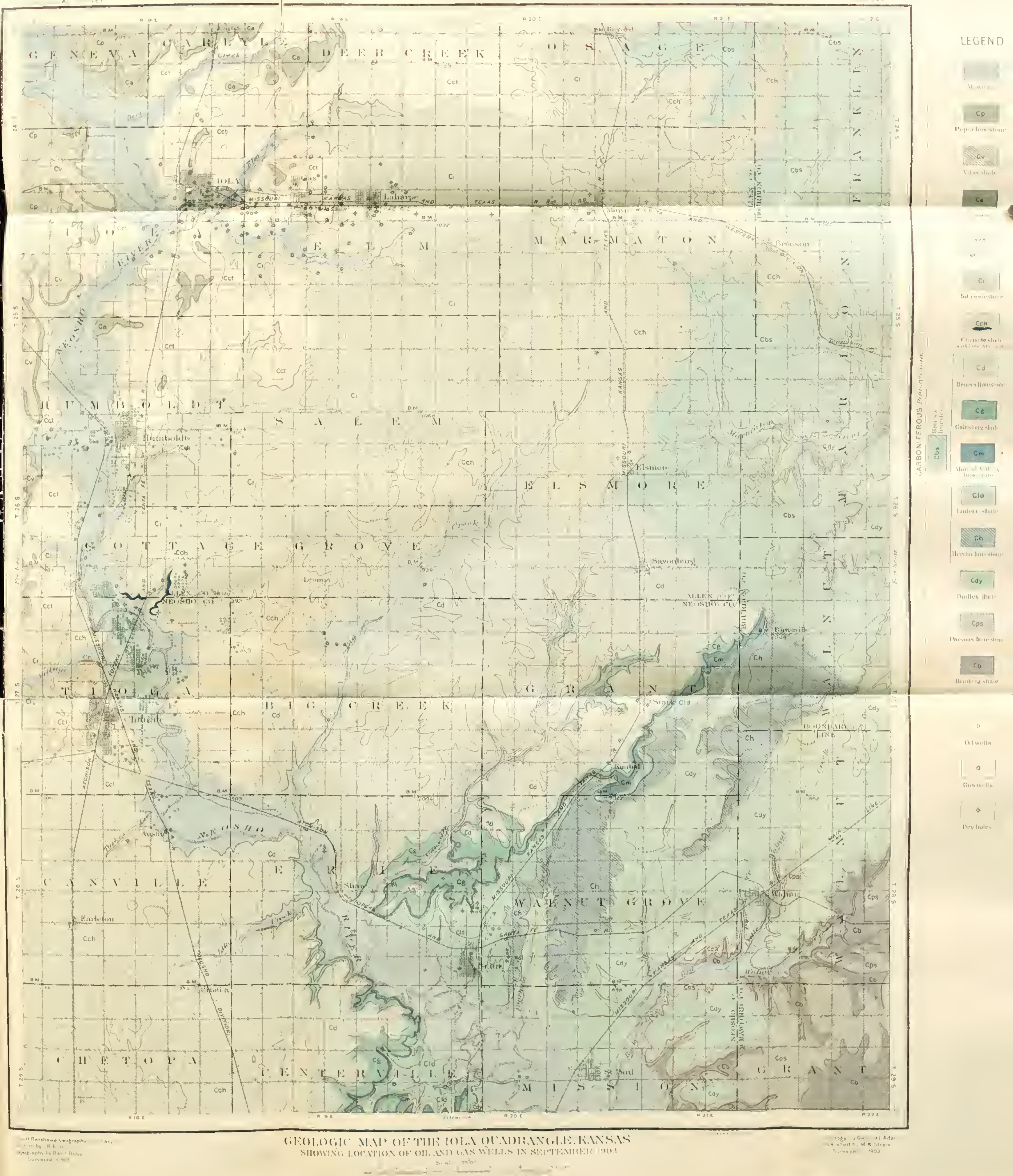
By George I. Adams.

SURFACE FEATURES.

The Iola quadrangle is situated in the prairie plains region, of which the eastern third of Kansas forms a portion. It has a moderate elevation, the lowest contour in the valley of Neosho River being 860 feet and in that of Marmaton River 880 feet above sea level, while the altitude of the higher points ranges from 1,000 to 1,080 feet. The surface features have been developed by erosion, and inasmuch as folding and faulting of the rocks are nowhere apparent, the topography is closely related to the strike and dip of the strata. The distinguishing features of this portion of the prairie plains are the low terraces and the occasional isolated hills or mounds.

The rock formations are interstratified shales, sandstones, and limestones, which have a northeast-southwest strike. As a result of erosion, the harder and more resistant beds produce escarpments which follow, with many deviations, the strike of the rocks. Inasmuch as the limestones are relatively more resistant in this area, they are found outcropping at the top of the escarpments and on the dip slopes. The dip of the rocks is to the northwest and varies usually from 10 to 25 feet per mile. In traveling northwest, where the country is not much dissected by streams, and in ascending the moderate terraces, one passes over the surface outcrop of successively higher beds. In going beyond the line of a particular escarpment one may travel several miles upon the surface of the same formation if stream valleys do not interrupt it; may do so, in fact, until he approaches the foot of the succeeding terrace. Where the drainage has dissected the country, particularly along the larger streams and their tributaries, the observer will readily note the surface features which indicate the dip of the rocks, and will see that the hills and bluffs form parts of sinuous escarpments.

The geology of the area is simple (Pls. I and II) and the fact that the country is not covered with forests renders observation easy. The uniformity of the general features, however, makes difficult the study of the detailed geologic structure, since definite folds are nowhere found and irregularities are taken up by minor and varying dips of the rocks.



GEOLOGIC MAP OF THE IOLA QUADRANGLE, KANSAS

SHOWING LOCATION OF OIL AND GAS WELLS IN SEPTEMBER 1903

Contour interval 20 feet

The rocks that outcrop in the Iola quadrangle and the oil and gas formations that are encountered in drilling (see Pl. III) belong to the Pennsylvanian series of the Carboniferous. This series is commonly spoken of as the Coal Measures, since it contains beds of workable coal, the important ones of which, in Kansas, are found in the lower portion of the section. Below the Coal Measures is the Boone limestone of the Mississippian series. In order to understand the relations of the strata below the surface in the Iola quadrangle, it is necessary to describe the formations which outcrop to the east and which are shown on the accompanying map (Pl. II).

DESCRIPTION OF FORMATIONS.

MISSISSIPPIAN SERIES.

Boone formation.—The Coal Measures rest upon the Mississippian series, which, in this region has commonly been designated the "Mississippian limestone" by those who have described or reported it in drill holes. The particular limestone formation spoken of under this name is in reality the Boone formation, which has its type locality in northern Arkansas. It outcrops over a large area in northern Arkansas, northeastern Indian Territory, and southeastern Missouri, and consists of limestone beds carrying a large amount of chert or flint, interbedded or occurring as rolls and lenses in it. In this formation are found the lead and zinc deposits around Joplin, Mo., and Galena, Kans. Within Kansas it outcrops in a small area between Spring River and the southeast corner of the State. Due east of the Iola quadrangle it is found in St. Clair, Cedar, and Dade counties in Missouri (see Pl. II).

The numerous wells that have been drilled in the Boone formation and the shafts and workings of mines, as well as the natural exposures of its outcrop, show that it is not an oil- and gas-bearing formation. In the oil and gas field this formation may be appropriately spoken of as the floor upon which the Coal Measures rest (see section accompanying Pl. II). It is encountered at a considerable depth in drilling, and when it is reached, as shown by the cuttings, drilling operations are usually stopped. A few wells within the oil and gas field have penetrated it for a considerable distance, notably a deep well at Neodesha, which probably passed entirely through it and into the underlying rocks. Its presence underneath the Coal Measures is pretty well established for the major portion of the field, and experience shows that there is no reason for expecting oil and gas after it has been reached.

The dip of the Mississippian limestone is to the northwest and, considered in its broader aspects, is even and regular. At certain places, however, the records of wells show that its upper surface is liable to present undulations and irregularities.

PENNSYLVANIAN SERIES.

Cherokee shale.—The lowest formation of the Kansas section of the Coal Measures is known as the Cherokee shale and has a thickness of about 450 feet. Although the term shale is applied to it it contains beds of sandstone which are, in some localities, of considerable extent and thickness. The area of outcrop is approximately 30 miles wide, and extends from Missouri across the southeast corner of Kansas into Indian Territory. Although some oil and gas have been found in the higher formations the Cherokee shale contains the important reservoirs in the Kansas-Indian Territory field. Where it outcrops there are occasional oil seeps, or springs, and deposits of maltha, or heavy oil, which have resulted from the surface oxidation and evaporation of the petroleum. Oil in economic quantity is found where the Cherokee shales are under sufficient cover to seal in and retain their contents of oil and gas. The dip being northwest, the shales are carried underground, so that within the principal oil- and gas-producing belt their upper portion is encountered at a considerable depth. Within the Iola quadrangle this depth increases from southeast to northwest, and is equal to the thickness of the overlying beds.

The records of numerous drill holes have been studied and from them it has been learned that the sandstone beds contained in these shales vary in character and thickness. In places they grade into more shaly material, so that it is impossible to identify the individual beds except in areas that have been closely drilled. Inasmuch as these sandstones are the principal oil and gas reservoirs close attention has been given to their character and extent. This subject will be discussed later in the report; here it is sufficient to state that no beds have been found which can be identified and given special designations, as has been done in certain fields where the oil sands are numbered or named.

Fort Scott limestone.—This limestone is the lowest persistent formation in the Kansas section of the Coal Measures. It is named from the town of Fort Scott, where it outcrops. It there consists of a lower limestone member 4½ feet thick (the rock used for making hydraulic cement at Fort Scott), and an upper limestone member from 10 to 14 feet in thickness, with usually a shaly member about 7 feet thick between the two. Although the Fort Scott limestone is a relatively thin formation it is easily traced in the field and has been identified from Fort Scott for a short distance northeast into Missouri and southwest into Indian Territory, its line of outcrop passing the towns of Girard, Cherokee, and Chetopa, Kans., and Chelsea, Claremore, and Catoosa, Ind. T. It lies just above the Cherokee shales and in the Kansas oil and gas field may be spoken of as the last Coal Measures limestone encountered in the wells.

GEOLOGIC MAP AND SECTION SHOWING STRUCTURAL RELATIONS OF THE OIL AND GAS-BEARING FORMATIONS OF THE IOLA QUADRANGLE, KANSAS

Scale

0 1 2 3 4 5 10 15 20 25 miles

1904

Note: Geology of the Iola quadrangle by George I Adams, assisted by M K Shaler. Geology of the Fort Scott quadrangle by Erasmus Haworth of the Univ Geol Survey of Kansas

Labette shale.—The Labette shale lies above the Fort Scott limestone and varies in thickness from 30 to 60 feet. Its outcrop forms an irregular belt, limited by the Fort Scott limestone on the southeast and the Pawnee limestone on the northwest. The shale carries relatively little sandstone and there is nothing that serves to distinguish it especially from the other shales of the series.

Pawnee limestone.—The second limestone formation is the Pawnee, which, on Pawnee Creek west of Fort Scott, has a thickness of 35 feet. According to the records of wells it varies from 20 to 50 feet in thickness. Its outcrop is shown on Pl. II.

Bandera shale.—Succeeding the Pawnee limestone is a bed of shales approximately 100 feet thick at its outcrop on Marmaton River near Bandera. Its thickness varies, however, with its lateral extent. Near Bandera it contains considerable thin-bedded sandstone, which is quarried for flagging; southwestward near Farlington and Brazilton it is similar in character. Its outcrop is shown on Pls. I and II; it is the lowest formation outcropping within the Iola quadrangle (Pl. I).

Parsons limestone.—The third limestone formation, counting from the base upward, is known as the Parsons limestone. Along Marmaton River it forms a bed 8 feet thick, but thickens southward. Within the Iola quadrangle it is found principally along Big and Little Walnut creeks, and on the higher ground to the southeast where it occupies irregular areas. Around Walnut and southward it has a thickness of from 10 to 15 feet and is regular in character.

Dudley shale.—Succeeding the Parsons limestone is the Dudley shale, with a thickness on Marmaton River of about 150 feet. It carries some sandstone and occasionally a thin layer of limestone. The outcrop of this formation is shown on Pls. I and II. This shale outcrops principally in stream valleys and occupies an irregular belt along Rock and Walnut creeks. Since it consists of soft beds and is easily eroded its upper limit and western border are defined by an escarpment which is quite conspicuous and in which occurs the succeeding limestone formation.

Bronson formation.—In the northeastern part of the Iola quadrangle, succeeding the Dudley shale, is a heavy limestone formation which has a thickness of from 60 to 80 feet. Its western outcrop forms a conspicuous escarpment along the head of Marmaton River. It consists of five members (see Pl. III). The lowest of these is an unevenly and heavily bedded limestone from 20 to 25 feet thick; succeeding this is a bed of shale, seldom more than 7 feet in thickness; next comes a middle member of limestone beds with some shale layers, aggregating about 20 feet where it is thickest; above this is a shaly member which grades into sandstones and has an average thickness of about 10 feet; the top member consists of limestones, the upper layer of which is in places a cross-bedded oolite, with an average thickness of 25 feet.

The detailed section of the Bronson formation varies from place to place as the character of the bedding of the limestone changes and as the shale members thicken and thin. These are so thin and inconspicuous in the northern part of their outcrop that they can not be mapped; they thicken southward, however, and become important enough to merit separate designation. On the geologic map of the Iola quadrangle (Pl. I) it will be seen that the pattern by which the Bronson is indicated is blended along a line extending approximately from Elsmore through Porterville, south of which five formations are shown as its equivalent. There are the Hertha limestone, Galesburg shale, Dennis limestone, Cherryvale shale, and Drum limestone, which are described below.

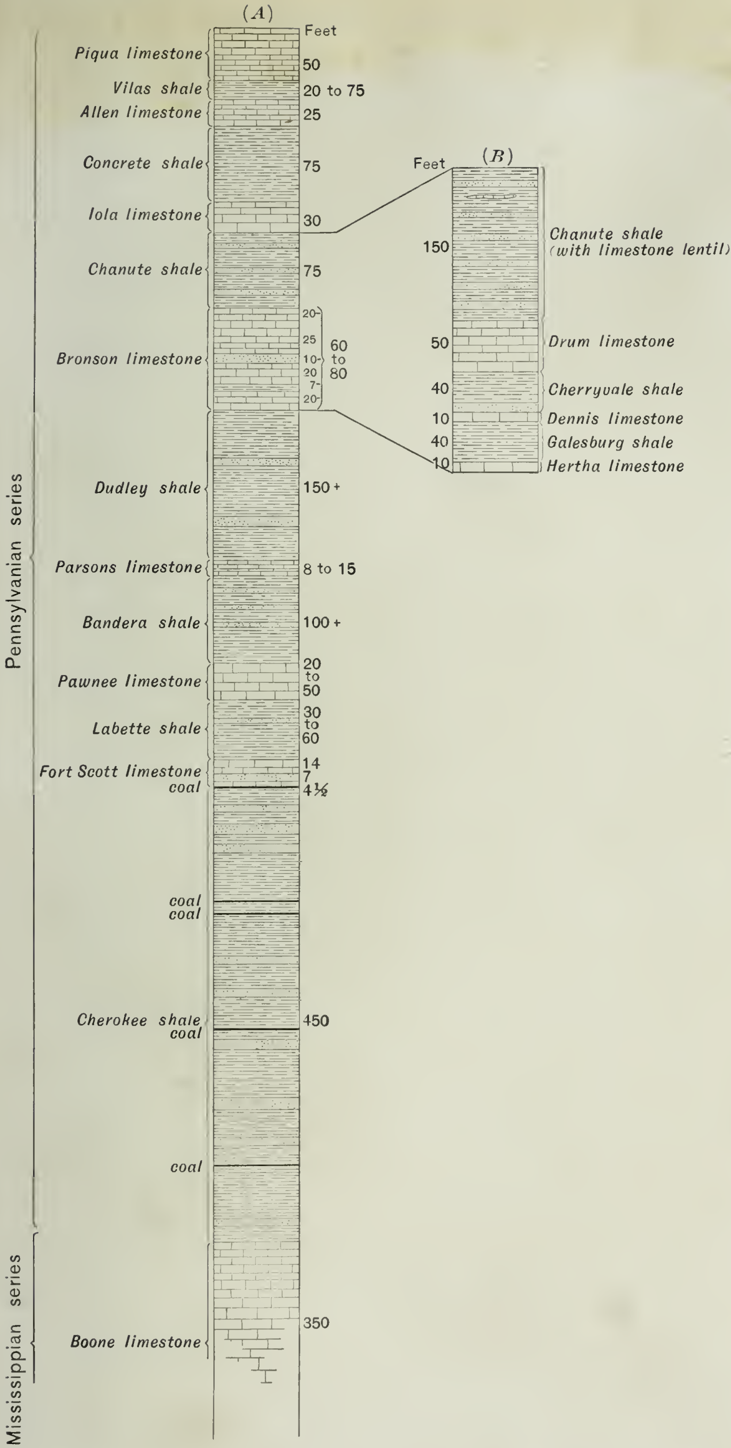
The Bronson limestone carries a large amount of chert in certain of its beds, and this, weathering out on the surface, forms the so-called flints which are found within the area of its outcrop. The surface of the country occupied by this formation is stony, the rocks protruding through the thin soil as bowlders. This is one of the heaviest limestone formations encountered in drilling for oil and gas in the northwestern part of the quadrangle, and is sometimes spoken of by the drillers as the 60-foot lime, no account being taken by them of the thin shale members which occur in it.

Hertha limestone.—This formation, which is named from the station of Hertha, just south of the border of the Iola quadrangle, has a thickness of about 10 feet at the type locality, thickening to the north. The eastern border of its outcrop forms a prominent escarpment to the northwest of Walnut, where it is found on a long ridge and has a thickness of as much as 20 feet.

Galesburg shale.—The northernmost point at which this formation is mapped is in the vicinity of Porterville. It increases in importance to the south, and has a thickness of about 40 feet along Neosho River and on the southern border of the quadrangle. Inasmuch as it is easily eroded the surface in that locality is cut down into an even plain, which blends with the alluvium along Neosho River. The town of Erie is located on it.

Dennis limestone.—This formation, which is equivalent to the middle member of the Bronson, thins somewhat to the south, having a thickness of only about 10 feet on the border of the quadrangle. North of Erie its outcrop occupies a very narrow belt, and as it usually occurs on a slope, is somewhat disguised by soil and detrital material.

Cherryvale shale.—This formation, although designated as a shale, carries some sandstone, especially in its lower portion. It thickens southward, the shale of the upper part becoming more important



GENERAL SECTION OF ROCKS EXPOSED IN THE IOLA QUADRANGLE AND ENCOUNTERED IN DRILLING.

at the southern border of the quadrangle it has a thickness of about 40 feet.

Drum limestone.—This formation, which is equivalent to the highest member of the Bronson limestone, outcrops with its maximum thickness in a wide belt in the central part of the Iola quadrangle. At Shaw the limestone is as much as 50 feet in thickness, thinning gradually from there southward. It is the surface formation along Big Creek and in the upper valley of Canville Creek; where it is weathered the surface is stony and bowldery. The Drum limestone carries a large amount of flint in its lower portion; the upper portion is an oolite which exhibits cross-bedding and false bedding, and attains a thickness in some places of as much as 15 feet.

In the northern portion of the quadrangle the 60-foot lime, spoken of by the well drillers, is the Bronson. In the southern portion of the quadrangle the Drum limestone is the one commonly referred to by this name, the Hertha and Dennis limestones being relatively thin and separated by the Galesburg and Cherryvale shales.

Chanute shale.—This formation, which succeeds the Bronson limestone in the northern and the Drum limestone in the southern part of the quadrangle, outcrops in a conspicuous belt extending from northeast to southwest. Although the rock section consists chiefly of shale, it carries a large amount of sandstone, and as this weathers out in ledges and on disintegration gives rise to sand, the country in which the formation occurs is generally sandy. The Chanute shale in the vicinity of Bayard, on the northern border of the quadrangle, is about 75 feet thick. In the southeastern part of the quadrangle it is about 150 feet thick and the belt occupied by it is correspondingly wide.

There are occasional outcrops of thin limestone beds in the Chanute shale which appear to occur in the upper part of the formation. Possibly they belong to a rather definite horizon, but the outcrops could not be connected in the field. Along the creek which crosses the Allen County–Neosho County line north of Chanute, is a bed of limestone which has a thickness of about 7 feet and which is mapped as a lens in the Chanute shale. It should be considered as of only local importance in the stratigraphy.

Iola limestone.—The thickness of this bed at Iola is 30 feet. It occurs as a massive-bedded limestone, and is the one which is quarried for making Portland cement. The principal area of its outcrop extends from Laharpe and Moran southwest to Humboldt and Chanute. Within this area it is covered by a variable thickness of soil, which frequently disappears, leaving the formation exposed and making the surface of the country stony. Along the eastern side of Neosho River, at Humboldt, it forms a high bluff in which practically its whole thickness is exposed.

This formation, like all the others described, dips to the northwest.

Its southeast border forms a divide between Big Creek and the head-waters of the Marmaton drainage on the one side, and the streams which are tributary to the Neosho from the east, above Chanute, on the other. On the upper surface of the limestone a dip slope is developed, which is well brought out by the contours of the topographic map. On Rock and Coal creeks there are inliers of the Chanute shale where the Iola limestone has been cut through. It is not unlikely that along some of the smaller streams and ravines erosion has also cut through the Iola at many places, but the Chanute shale is not seen because of the covering of soil on it. In drilling wells in the area which is mapped as the Iola formation, at many places only a few feet of the limestone are encountered, and in some cases it is found to be absent. This, as has just been explained, is due to erosion.

Concreto shale.—Succeeding the Iola limestone is a bed of shale having a thickness of about 75 feet. It is uniformly a clay shale, and accordingly is suitable for the manufacture of brick, and, with the admixture of limestone, for Portland cement, for which it is used at Iola and at the small manufacturing town of Concreto, north of the town of Gas. Within the area of its outcrop are a number of mounds formed of this shale and capped with the succeeding limestone formation. The western border of the valley of Neosho River, from the vicinity of Iola southward to a point below Humboldt, lies on this shale, and the alluvium along the streams blends with the outcrop of the shale to the west in a somewhat indefinite way.

Allen limestone.—In the vicinity of Carlyle this limestone formation has a thickness of about 25 feet. It thins to the south gradually, so that it has a thickness of about 10 to 15 feet along the western border of the quadrangle. Its outcrop forms a narrow belt west of Neosho River. It is difficult to trace at many places, but its position has been determined by studying the records of wells. A number of irregular areas of this formation occur to the east of Neosho River, capping hills and mounds.

Vilas shale.—The type locality of this formation is at Vilas, where the shale has a thickness of about 75 feet. This formation, which has previously been wrongly correlated, is now known to lie between the Allen limestone and the Piqua limestone, which latter formation is described below. The Vilas shale thins somewhat to the north, so that near the northern portion of the quadrangle it is not more than 20 feet thick.

Piqua limestone.—This is the highest formation exposed within the Iola quadrangle. It consists of heavy-bedded limestones, having a total thickness of about 50 feet. It occurs only in the northeast corner of the quadrangle, but beyond the area here described outcrops conspicuously for long distances to the northeast and southwest. It was traced to the vicinity of Vilas, at which place it overlies the Vilas shale.

ALLUVIUM.

Along the valley of Neosho River and the larger streams which are tributary to it is a belt of alluvium deposited by the overflow of the streams during flood time. It consists of river silts derived from the limestones, shales, and sandstones which are crossed by the streams, and is rich agricultural land.

From the vicinity of Chanute southward dikes have been constructed to prevent the overflow of the river and thus render the land available for farming. The alluvium along the creeks is not of much importance. There are, however, small fields which have an alluvial soil, and in some portions of the quadrangle where alluvium is not mapped there are small areas of it which are cultivated.

The cherts of the limestones upon disintegration give rise to gravel, which is found mixed with the soil near the ledges of rock from which it is derived and at places where the limestones have entirely wasted away. These gravels have also been transported by the streams and deposited in beds. These are not of much importance outside of certain gravel bars along Neosho River, which have been utilized for grading roads. The main street of Humboldt has been macadamized with this material.

CORRELATION AND CORRECTION OF FAUNAL LISTS.

The mapping accompanying this report is regarded as the first systematic detailed work in the region, and accordingly the formation names used are such as can be applied without involving correlations with distant localities. This has made it necessary to give new names to some formations which have been previously described. Some errors in correlation, discovered in former work, have been corrected in this bulletin and the faunal lists of certain of the formations revised accordingly.

In Bulletin No. 211[a] of the United States Geological Survey a section of the Carboniferous of eastern Kansas is given in detail. The changes in nomenclature which have arisen since that bulletin was issued are as follows: In the northern part of the quadrangle the Hertha, Galesburg, Dennis, Cherryvale, and Drum formations are mapped as a single formation under the name Bronson limestone, for which the preoccupied name Erie had been previously used. The Earlton limestone has been found to be the equivalent of the Iola limestone and the name Earlton is accordingly dropped; the shale previously described as the Lane shale is called the Concreto shale; the Stanton limestone is called the Allen limestone. The Vilas shale at the type locality has been found to be above the Allen limestone;

[a] Adams, Girty, and White, Stratigraphy and paleontology of Upper Carboniferous rocks of Kansas section: Bull. U. S. Geol. Survey No. 211, 1903.

this name is retained, and the position of the formation in the section is accordingly corrected. The limestone which occurs above the Vilas shale is found to be a new limestone formation to which the name Piqua is given. The error in correlation of this outcrop, as well as the error in tracing the Earlton limestone, was due to the fact that the relatively broad valley of Neosho River made the reconnaissance mapping difficult. The following columnar section is the one used in this bulletin

Formations exposed in Iola quadrangle.

Alluvium.	
Piqua limestone.	
Vilas shale.	
Allen limestone.	
Concreto shale.	
Iola limestone.	
Chanute shale.	
Drum limestone.	Bronson formation.
Cherryvale shale.	Bronson formation.
Dennis limestone.	Bronson formation.
Galesburg shale.	Bronson formation.
Hertha limestone.	Bronson formation.
Dudley shale.	
Parsons limestone.	
Bandera shale.	
Pawnee limestone.	
Labette shale.	
Fort Scott limestone.	
Cherokee shale.	

The corrected faunal list of the Iola limestone as now known is as follows:

Fossils found in Iola limestone.

Eupachycrinus sp.
Fistulipora sp.
Fenestella sp.
Chonetes flemingi.
Productus cora.
Productus punctatus.
Marginifera wabashensis.
Spirifer cameratus.
Spiriferina kentuckyensis.
Seminula subtilita.
Dielasma bovidens.
Aviculopecten interlineatus.
Phanerotrema grayvillense.

The corrected faunal list of the Allen limestone as now known is as follows:

Fossils found in Allen limestone.

Lophophyllum westi.
Eupachycrinus sp.
Archæocidaris sp.
Polypora sp.
Fenestella sp.
Fistulipora sp.
Rhipidomella pecosi.
Enteletes hemiplicatus.
Orthotetes crassus.
Chonetes flemingi.
Productus nebraskensis.
Productus punctatus.
Marginifera wabashensis.
Spirifer cameratus.
Squamularia perplexa.
Spiriferina kentuckyensis.

Seminula subtilita.
Hustedia mormoni.
Pugnax utah.
Dielasma bovidens.
Platyceras nebraskense.
Bellerophon sp.
Phillipsia major.

The corrected faunal list of the Piqua limestone as now known is as follows:

Fossils found in Piqua limestone.

Triticites secalicus.
Lophophyllum westi.
Lophophyllum proliferum.
Chætetes milleporaceus.
Eupachycrinus sp.
Septopora sp.
Fenestella sp.
Polypora sp.
Fistulipora sp.
Crania sp.
Rhipidomella pecosi.
Enteletes hemiplicatus.
Orthotetes crassus.
Meekella striaticostata.
Meekella pyramidalis?
Chonetes flemingi.
Productus semireticulatus.
Productus cora.
Productus punctatus.
Productus nebraskensis.
Productus cf. subhorridus.
Productus sp.
Marginifera wabashensis.
Proboscidella sp.
Spirifer cameratus.
Squamularia perplexa.
Spiriferina kentuckyensis.
Seminula subtilita.
Dielasma bovidens.
Myalina subquadrata.
Myalina swallowi.
Pseudomonotis equistriata.
Schizodus sp.
Leda? sp.
Soleniscus ponderosus?
Naticopsis sp.
Euconospira sp.
Pleurotomaria? sp.
Nautilus sp.
Leperditia sp.

GENERAL STRUCTURE.

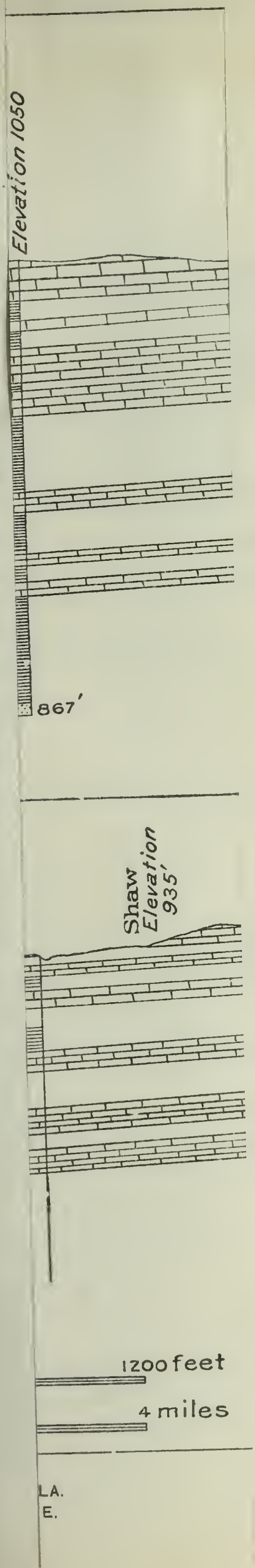
The general structure of the rocks of the Iola quadrangle may be best explained by the horizontal section accompanying Pl. II. The dip of the rocks is to the north-northwest, and accordingly the portion of the section along the line *A-B* is approximately parallel with the dip. It will be seen by reference to the section that the wells at Iola and Laharpe penetrate a considerable thickness of interstratified limestones, sandstones, and shales before reaching the Cherokee shale, which contains the important reservoirs of oil and gas. The wells in the vicinity of Elsmore encountered a somewhat smaller thickness of these rocks, and the drill holes at Hepler and in the vicinity of Farlington reached the Cherokee shale at a relatively small depth. The outcrop of the Cherokee shale is farther to the east and occupies a wide belt of country. Along the eastern border of the map (Pl. II) the outcrop of the Boone formation is shown; in the section its extension underneath the Cherokee shale to the west and northwest is indicated. Its position underground has been learned from the record of deep wells which have been drilled through the Cherokee shale without encountering oil and gas, and its upper surface is known to form a rather even floor, on which the Coal Measures rest. In Pl. IV two sections are shown, which are constructed from the records of wells and the surface outcrops of the formations. The section through Moran, Laharpe, and Iola extends east and west in the northern part of the quadrangle, and the section through Erie, Shaw, and Chanute extends from southeast to northwest in the southern part of the quadrangle. In these sections the limestones are indicated by conventional patterns; the intermediate spaces are the horizons of the shales. In these sections, although the vertical exaggeration is very considerable, no anticlines or synclines appear. The degree of dip which was observed in the field varies from place to place in such an irregular manner that the local variations are not apparent in the sections. The amount of dip may be stated to vary from 10 to 25 feet per mile. The limestones are not exactly parallel with each other, this being due to the irregular thinning and thickening of the shale beds. Certain of the well sections record a greater number of limestones than there are limestone formations in the general section. The Bronson limestone, when followed south through the quadrangle (see Pls. I and II), is found to split up into three distinct limestone formations, with intervening shale beds, which are important enough to map. This variation in lithology occurs along the strike. It is altogether probable that, if the limestones could be studied along their dip in their extent underground to the west, some of them would be found to split up in a similar manner, at least locally, and when in drilling more limestones are encountered than are recorded in a general section it is probable that the extra ones are due to such variations in sedimentation.

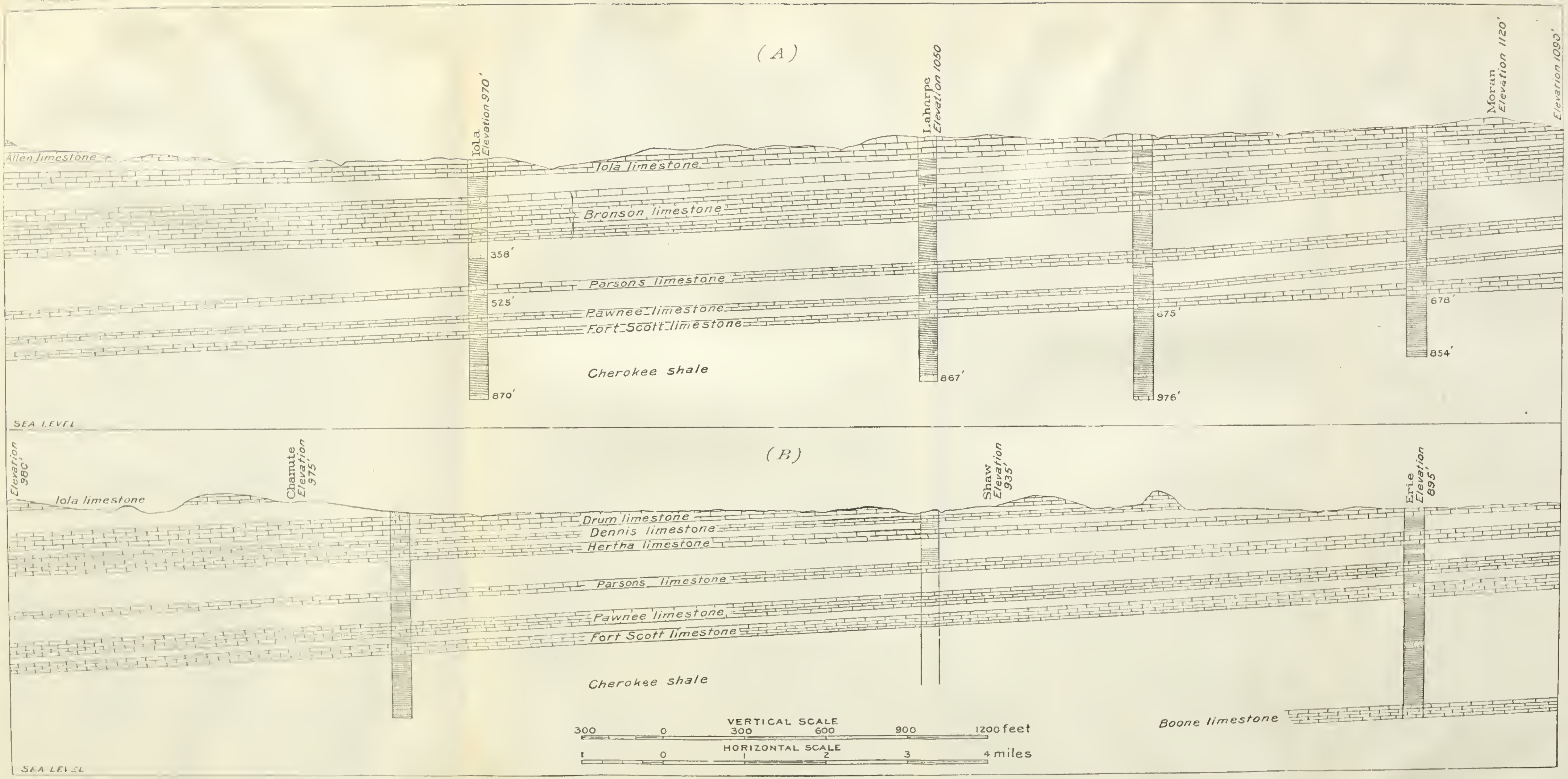
It will be remembered that in describing the Chanute shale a limestone lens of sufficient importance to be shown on the geologic map was mentioned as occurring in its upper part. Similar lenses no doubt occur in this and other shale formations in their underground portions, and accordingly the finding of thin limestones at unusual horizons is not surprising.

ORIGIN OF OIL AND GAS.

The processes by which oil and gas are formed in nature are not fully understood. Two hypotheses, known as the organic and inorganic theories, have been advanced. In the Kansas field the facts support the organic theory, which is the one usually accepted by geologists who have studied the relations of oil and gas.

The rocks which are encountered in drilling in the Kansas field, especially the shales, contain large amounts of carbonaceous matter of animal and vegetable origin that was deposited at the time the sediments were laid down. This material is present in sufficient quantity to have given rise to the oil and gas through the processes of decomposition and the physical and chemical changes to which it has been subjected during geologic time. When once formed the products of


Elevation 1050
867'
Shaw
Elevation
935'
1200 feet
4 miles
LA.
E.



A. GEOLOGIC SECTION THROUGH MORAN, LAHARPE, AND IOLA
B. GEOLOGIC SECTION THROUGH ERIE, SHAW, AND CHANUTE.

decomposition probably migrated into the more porous rocks, especially into the sandstones, in which they are now found. No doubt a large amount of the oil and gas has escaped from the formations where these outcrop at the surface. The economic bodies are those which are completely sealed in by impervious shales with which the sandstones are interbedded. There are no surface indications of oil and gas in the more productive portion of the field. The Cherokee shale, which contains most of the oil and gas sands, outcrops along the eastern border of Kansas and in Missouri, where there are occasional seeps of gas, oil, and maltha, the latter being a heavy residual from oil. These seeps have attracted the attention of prospectors and some drilling has been done near them, but, inasmuch as they occur where the rocks outcrop, no large bodies of oil or gas have been discovered in their vicinity.

The question of the movement of oil and gas is one which is not well understood. It is generally believed, however, that where oil, gas, and water are found in a given stratum, the oil and gas will move upward with the dip of the rocks until they enter a pocket or escape to the surface. In the Iola quadrangle the oil and gas sands are of local extent and are interbedded with the shale in such a way that where they are deeply buried they form perfect reservoirs. The dip of the formations is to the northwest. Accordingly the oil and gas may be expected in the higher or southeastern extension of the sandstone beds; the heavier salt water will border these deposits on the northwest. These conditions, though somewhat ideal, are found in many places, and variations from them are due probably to slight irregularities in the dip of the rocks and to changes in the character of the sediments which bring in unknown and undeterminable factors. The upper margin of an inclined or dipping sandstone is the simplest form of reservoir and no doubt is the common one in the Kansas field (see fig. 6, *A*, p. 46). In other fields the accumulation of oil and gas is determined by folds, or synclines and anticlines, as they are usually called. These may occur locally in the Kansas field, but it has been impossible to locate definitely any anticlines or upward archings of the oil- and gas-bearing strata.

RELATIONS OF THE OIL- AND GAS-BEARING SANDSTONES.

Inasmuch as the oil- and gas reservoirs are in the sandstones interbedded with the shales, the question arises as to whether these sandstone beds form definite horizons. Well drillers and prospectors who have had experience in the Pennsylvania oil and gas field, on coming into the Kansas oil and gas field have attempted to name or number the producing sands and to identify them throughout the field. As will be seen from the following discussion this can not be done because of the very irregular and local character of the sandstone beds.

The principal reservoirs of oil and gas are in the Cherokee shale. This formation has been studied along the eastern border of Kansas where it outcrops, and it has been found that the sandstones in it vary in their lateral extent and in many cases are of very limited occurrence. Sometimes they grade into shales when followed along their outcrop, so that a bed which is sandstone at one place is a shale at another. The same variation that is found along the strike may be expected along the dip, and accordingly the Cherokee shale, where it occurs underground and is encountered in drilling wells, shows such variation in lithology that no definite sandstone horizons can be differentiated.

Fig. 2 is an ideal sketch of the relation of sandstones contained in a shale formation. In this figure the sandstone lettered *a* is lenticular in shape, it thins out and disappears entirely from the section, and has no equivalent. The sandstone lettered *b* is shown to grade over into a shale which is its equivalent. Sandstone *a* is apparently

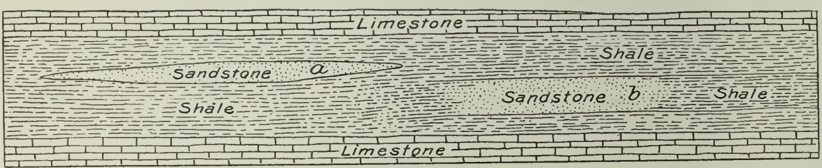


FIG. 2.—Sketch illustrating disappearance of sandstone beds; *a* is a lenticular sandstone which disappears by thinning; *b* is a sandstone which grades into shale.

the result of sedimentation at a time when only sand was being deposited. Sandstone *b* apparently represents a period of sedimentation in which both sands and muds were being laid down, according to the local variation in the strength of the currents which assorted the material. As regards these two classes of sandstones, observations have shown that the lens-like beds are apt to be more persistent and to extend for longer distances, while the sandstones which grade into shales vary from place to place in an exceedingly irregular way.

The irregular area of the sands encountered in drilling may be shown by the following instances: In fig. 3, the relative positions of certain wells are sketched and a portion of the record of each is shown drawn to scale. The wells are in secs. 26 and 27, T. 26 S., R. 18 E., about 4 miles southeast of Humboldt. The wells in sec. 26 belong to the Oread Oil and Gas Company and those in sec. 27 to the Kansas Crude Oil Company. The well called Kansas Crude No. 1 was drilled to a total depth of 880 feet. At 768 feet, 10 feet of sand was found which was practically barren of oil. At 833 feet, 5 feet of sand was found which was rich in oil, and at 844 feet, 12 feet of sand was encountered that was productive. The base of this sand was at 856 feet.

Below this point 16 feet of shale was passed through, then 5 feet of sand, which produced close to 1 million feet of gas per day. The drill went 3 feet farther in light-gray shale and was then stopped.

Oread well No. 1 is situated 300 feet due east of the well just described. In it 8 feet of sand rich in oil was encountered at 764 feet, corresponding fairly well with the 10 feet of sand in the Kansas Crude well. Below it 62 feet of shale was passed through and then 14 feet of productive oil sand, corresponding very well with the 12-foot bed of sand in the first well described. After passing 9 feet in shale the drill was stopped, as it was not desired to reach the gas which, according to the record of the Kansas Crude well, might be expected below.

Oread well No. 2 was located 400 feet south of Oread No. 1. At a depth of 798 feet 25 feet of sand was found which produced a large

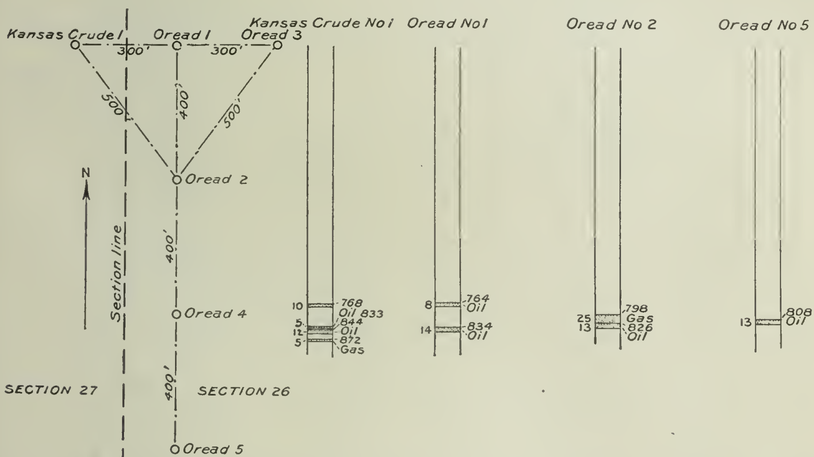


FIG. 3.—Relative positions and partial logs of certain wells of the Kansas Crude Oil and the Oread Oil and Gas companies.

quantity of gas. Below this 4 feet of black shale, partly saturated with oil, was passed through, and then 13 feet of productive oil sand, the bottom of which was 839 feet below the surface. It will be noted that in this well no sandstone was found at a depth of 770 feet where, according to the records of the other wells, it might have been expected, while a bed of gas-bearing sand 25 feet thick was encountered at 798 feet, no trace of which was found in either of the other two wells.

The next well drilled was Oread No. 3, which was located 300 feet east of Oread No. 1. In it no oil was found, but a strong flow of gas was obtained from a sand at a depth of about 800 feet, doubtless corresponding to the gas sand found in well No. 2.

Well No. 4 was located 400 feet south of No. 2. In it a productive oil sand was reached at 835 feet, corresponding to the oil sand in the other three wells.

Well No. 5 was located 400 feet south of well No. 4. At 800 feet a small flow of gas was obtained, and at 808 feet 13 feet of productive oil sand was encountered, corresponding with the oil sands in the other wells.

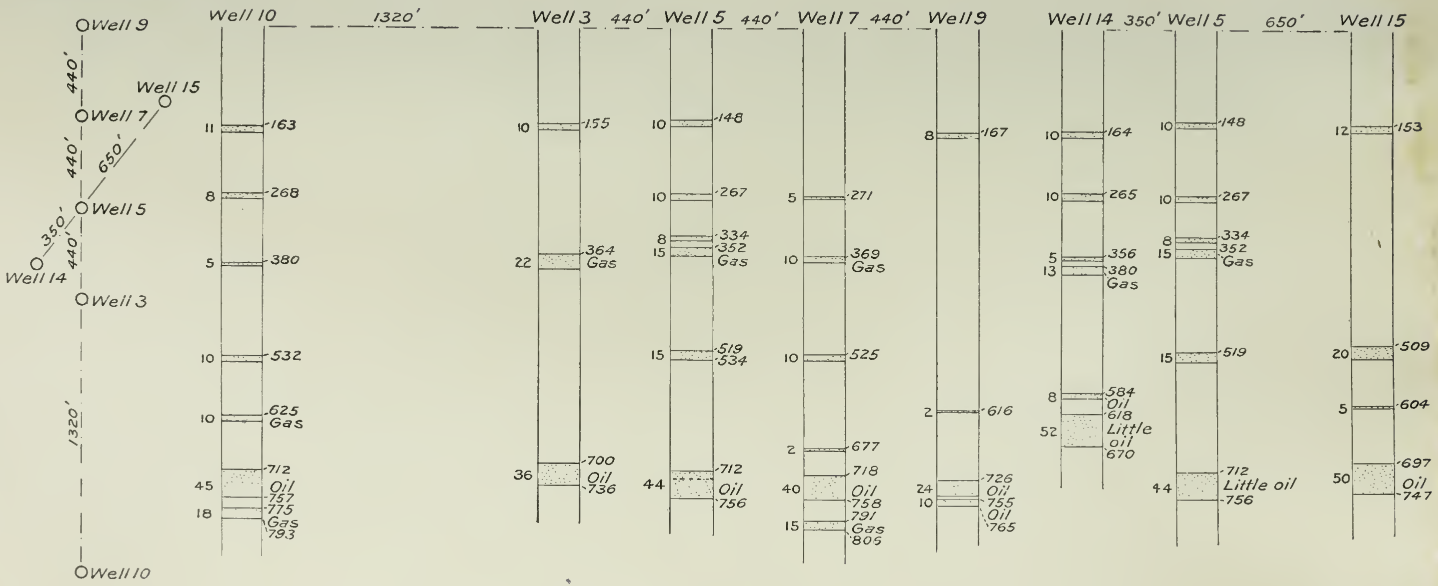
Reviewing what has been stated concerning these six wells it is seen that there is a sandstone 10 feet in thickness in Kansas Crude No. 1, which disappears entirely in a distance of less than 600 feet to the east, and less than 500 feet to the southeast, as it is totally wanting in Oread Nos. 2 and 3. The 25-foot gas sand in Oread No. 2 is not represented in Oread No. 1, or in the Kansas Crude No. 1. This illustrates the rapid transition in the character of the strata.

In regard to the gas horizons it will be noted that a strong flow of gas was obtained from a sand lying beneath an oil sand in Kansas Crude No. 1, and that the stronger flow of gas was obtained from a sand above the oil sand in Oread No. 2, only 500 feet away. It is impossible to say what would have developed in Oread No. 3 had the drill gone deeper, but the main oil sand might have been reached. Likewise, it is impossible to determine whether the Oread wells, if they had been drilled deeper, would have reached the gas at 875 feet, the depth at which it was encountered in Kansas Crude No. 1.

The discussion of the records of the wells in sections 32 and 33 in T. 26 S., R. 18 E., in the valley of Neosho River between Humboldt and Chanute, furnish further illustration of the variation in the horizon and lateral extent of the oil and gas sands. In SE. ¼ sec. 32, the Kansas and Texas Oil Company drilled a dry hole. Later they completely surrounded this well with others not more than 350 feet away, all of which were producing oil wells. Some wells not more than 500 feet distant had an initial production of 300 barrels per day. In SW. ¼ sec. 33, which is adjacent, a large number of good oil wells were found with a gas well but a few hundred feet away.

In Neosho River Valley, east of Chanute, the oil is generally, but not always, above the gas. In most instances the oil sand is reached at from 700 to 750 feet. Usually there is a bed of shale about 40 feet thick below the oil sand, and beneath this a heavy bed of sand carrying large quantities of gas. The first gas wells at Chanute went through the oil sands, and it was their showing of oil that induced Mr. Knapp to begin drilling for oil in the Chanute field. The gas wells there had an initial capacity of from 1,000,000 to 4,000,000 cubic feet per day, and others recently drilled a mile or more to the east across the river had an even greater initial flow. From the sandstone, only 40 feet above this large volume of gas, oil was produced having so little gas with it that the pressure was not sufficient to cause the wells to flow, thus showing conclusively that there is no communication between the two sands.

In the east side of the W. ½ SW. ¼ sec. 22, T. 27 S., R. 18 E., in



RELATIVE POSITIONS AND PARTIAL LOGS OF WELLS JUST EAST OF CHANUTE, KANS.

the river valley just east of Chanute, Mr. Knapp drilled five wells on a north-south line. The records of these wells were carefully kept, as were the records of two wells, one on either side of this line (see Pl. V). The lower portions of the logs of these wells, showing the sandstones encountered, are presented, drawn to a scale, in Pl. V. The relative distance between the wells is indicated on the diagram and in the arrangement of the well sections. The surface is almost level, as the wells are in Neosho Valley, where the slope is not more than 2 or 3 feet to the mile. A glance at Pl. V will show the irregularity in the horizons at which the sands were encountered. In some cases the records of adjacent wells correspond closely in regard to particular sands, but it will be noted that some of the sands which are well marked in certain wells are wholly absent in others.

Inasmuch as the information is presented graphically, it is not discussed here. However, it leads to the conclusion that the individual sands are irregular in extent and character, and that they are exceedingly variable in regard to their contents of oil and gas. When both oil and gas are found in the same well the gas-bearing sand may be above or below the oil. Gas is generally more abundant than oil and has been found in a larger number of places; there are also usually more gas sands than oil sands in individual wells.

MINERAL RESOURCES AND THEIR UTILIZATION.

By Erasmus Haworth and George I. Adams.

OIL AND GAS.

HISTORICAL.

Iola and Laharpe.—The first prospecting for oil and gas within the Iola quadrangle was done at Iola in 1873, by Colonel Acers, who had a well drilled with a diamond drill to a depth of 737 feet. It produced a small amount of gas and also salt water. The water was conveyed into a building used for a sanitarium, which the gas, imperfectly separated, was used in part to light. Shortly after this a local company, consisting principally of the leading business men of Iola, was formed to drill for gas. It was regularly incorporated under the laws of Kansas, and obtained a charter from the city of Iola permitting it to pipe the city for the distribution of natural gas for public and private uses.

The first well, located in the river valley west of town, reached a depth of nearly 1,000 feet, but produced only a small amount of gas. The second well, which was near the main road leading west from Iola and not far from Neosho River, found a little gas, but not enough to be of very much importance. A third well, drilled a short distance southeast of where the Lanyon zinc smelter now stands, proved to be the best obtained up to that time, yielding a flow of 750,000 cubic feet of gas per day. Unfortunately it was drilled a little too deep, striking a large amount of salt water which rendered it almost useless. After drilling a fourth well with similar ill success the company sold its leases and franchise to Messrs. Paullin and Pryor, who assumed all the contracts of the old company.

The new owners drilled their first well just south of the Northrup lumber yard, on the south side of Madison street near the Sante Fe right of way. This was followed by three other wells in the southwest part of the city. The last one, finished in December, 1893, obtained a strong flow of gas, and is the only well of the first eight drilled at Iola which produced gas enough to pay for the drilling. A period of twenty years was covered by this prospecting and many thousands of dollars were spent, but success was finally attained.

One of the most interesting points in connection with the development of oil and gas in Kansas, not only in the Iola quadrangle, but elsewhere as well, is the very remarkable fact that in almost every instance the first prospecting was practically a failure and extended along through a number of years, to be followed by the work of new companies whose efforts were more successful. Messrs. Paullin and Pryor, however, were successful before they sold out. They drilled another well in 1895, obtaining a large flow of gas which at once gave Iola prestige as a gas-supplied city.

About this time a new company, known as the Iola Cooperative Gas Company, drilled a well southeast of the city, which developed into one of the strongest wells in the entire Iola field. The company piped its gas into the city and placed it upon the market. Litigation at once sprang up between it and Paullin and Pryor, who claimed to have an exclusive franchise. The final outcome was that Messrs. Paullin and Pryor sold out to the new company in 1898, and the two properties were consolidated under the name of the Iola Gas Company. This is the only company that has retailed gas in Iola since that date.

In 1894 the Palmer Oil Company of Ohio obtained leases in the vicinity of Iola and began prospecting. The first well was drilled to the southeast of the city, and yielded over 7,000,000 cubic feet of gas daily. Other wells were drilled to the east and northeast, until within a few years the Palmer Oil Company owned a great number of strong gas wells, some of which had a capacity of more than 10,000,000 cubic feet per day. In March, 1899, they sold their entire interests to the Lanyon Zinc Company, a new corporation which bought the smelters and leases from Robert Lanyon's Sons and from W. & J. Lanyon. Encouraged by the successful wells to the southeast, certain citizens of Iola formed a company known as the City Improvement Company, which had for its objects the bringing of desirable manufacturing enterprises to Iola. In furthering this undertaking they offered free gas to any and all reliable manufacturers for a period of twenty years, provided the gas supply continued. Attracted by this liberal offer, brick plants, smelters, flouring mills, and planing mills were soon built, with the result that Iola, Gas, and Laharpe to-day contain more large factories and industries consuming gas than any other locality in the State.

Prospecting for gas was carried eastward until it was learned that good gas could be found throughout a strip 8 to 10 miles long from east to west, and 4 to 5 miles wide; the north and south limits of the area have not yet been fully outlined.

Humboldt.—Guffey and Gailey were the first prospectors to drill wells in the vicinity of Humboldt. In 1894–95 they drilled a number of wells in this territory, not one of which proved very successful. One was in sec. 8, T. 26 S., R. 18 E., about 1½ miles southeast of Humboldt. A few others were drilled to the north of the town. These wells either were dry or produced a small amount of heavy oil; so that they were not considered worth holding and the leases were abandoned later. In 1901 Mr. George Z. Work drilled a well on his land about 100 yards west of the Missouri, Kansas and Texas Railway station at Humboldt. This well produced about 25 barrels per day of a rather heavy oil, having a specific gravity of about 30° Baumé. Some years earlier, under the direction of the city school board, a well was put down in the corner of the schoolhouse grounds in the southern part of the town. It passed through an oil sand of undetermined capacity and reached a supply of gas, which was used for lighting and heating the school building. A few other wells were drilled, but no important development work was done until the recent development at Chanute, when prospectors again began drilling in the vicinity of Humboldt, and have continued with ever-increasing activity up to the present time. Drilling was first confined to the river valley west and south of town, but later it was extended to the uplands, particularly to the east, and soon reached the entire upland area to the east and southeast of Humboldt, particularly in T. 26 S., R. 18 E., and in the western part of R. 19 E. From here, during the season of 1903, development was carried southward on the uplands to opposite Chanute, making the upland development in the two areas progress along parallel lines.

During the spring and summer of 1895 the Prairie Oil and Gas Company drilled a number of wells west of Humboldt, which produced enough gas to have considerable commercial value. In August, 1897, the gas was piped into the city for general domestic use. The supply was not very large, however, until the rapid drilling for oil began, as above explained. About this time large quantities of gas were obtained, practically in all directions from town, so that at present Humboldt is well supplied.

Chanute.—The history of oil and gas development in the vicinity of Chanute is an interesting and checkered one. In 1894, Guffey and Gailey put down one or two prospecting wells, but, finding nothing, the territory was abandoned and a large acreage of leases given up. Later, the Prairie Oil and Gas Company obtained a strong gas well about 16 miles to the west and laid pipes into Chanute to supply the city with gas. This, in connection with discoveries made elsewhere in the State, stimulated the people of Chanute to continue their investigations. The city took up the matter and drilled a few wells in Neosho Valley to the east of the town. They met with fair success, each well passing through an oil sand at about 730 feet. After passing through 40 feet of shale, the drill reached a gas sand which yielded from 1 to 4 million cubic feet of gas per day. Drilling was continued by the city until a satisfactory supply of gas was obtained for lighting and heating. It is interesting to note that this is the only city in the

GOLDEN OIL COMPANY'S WELL NO. 2, NEAR CHANUTE, KANS.

entire oil and gas fields of the State that owns its gas supply. It has made very low rates, as shown later, and yet derives sufficient income to make many municipal improvements.

While investigating the Kansas oil fields in 1899 Mr. I. N. Knapp had his attention called to the oil in these city gas wells. Considering the showing sufficiently favorable to warrant him in prospecting for oil, he obtained leases over quite a wide area and began prospecting both east and west of the city of Chanute. It was but a short time until he had a number of fair oil wells in the valley east of the town, and in June, 1900, he began shipping oil to Omaha and Kansas City gas companies, with which he made contracts. This was really the beginning of the oil development in the vicinity of Chanute.

Mr. Knapp was followed by a company composed principally of local business men and citizens of Iola, who organized the Neosho Valley Development Company, obtained leases, and began drilling. They had fair success from the start and soon had a number of producing wells. They were soon followed by a company composed principally of Kansas City business men, who organized the Southwestern Development Company, which likewise secured leases in the river valley and met with fair success in obtaining oil. From this time on the development was rapid. At the end of a year there were derricks and pipe lines all along the river valley to the east and north of Chanute and halfway to Humboldt. In the midsummer of 1902 the Prairie Oil and Gas Company built a large storage tank at Chanute with a capacity of almost 40,000 barrels. This was followed by a pipe line between Thayer and Chanute which, joined to the Neodesha-Thayer pipe line, gave Chanute a direct pipe line connection with the Standard refinery at Neodesha. A pump was established and the first oil turned into the line about the middle of December, 1902. The Prairie Oil and Gas Company at this time began extending its lines to oil tanks here and there all through the field. By July, 1903, these had reached as far north as Humboldt and had been carried eastward to the upland developments to the east of Humboldt and northeast of Chanute. During the calendar year 1902 the Chanute territory produced over 165,000 barrels of oil, and could have marketed much more if there had been pipe-line connections. In the first half of 1903 the production was raised from 50,000 to 75,000 barrels per month, with the number of wells constantly increasing.

Development was gradually extended southward down the river, with only moderate success, in the vicinity of Austin. A few fair oil wells wese obtained in the vicinity of Shaw. Still farther south a few good wells had been obtained near Urbana and Earlton and in the territory lying to the northeast of Thayer, in the extreme southwest corner of the Iola quadrangle. Gas development likewise extended rapidly in different directions, but particularly to the east and west, making Chanute a great center for gas as well as for oil.

Erie.—Prospecting began in the vicinity of Erie about 1900, but was carried on in a somewhat desultory way until 1902. About this time a company was organized under the name of the Erie Gas and Mineral Company. In August, 1903, it reported that it had drilled 35 wells, 14 of which were gas wells, 7 oil wells, and 14 dry. The gas was piped into the city and supplied practically the entire population. During the summer of 1903 some prospecting was done in the river valley between Shaw and Erie, and, in some cases, gave very satisfactory results, but up to the date above mentioned, nowhere to the southeast of Chanute had oil or gas been found in quantity or volume at all comparable with that in the Chanute and Humboldt fields.

Moran.—The Moran Gas and Crude Oil Company began prospecting in the vicinity of Moran and soon found oil in paying quantities. The territory drilled to the close of the season of 1903 consisted almost entirely of a strip of land about 1 mile wide and 2 miles long lying immediately west of the town. Of the first 19 wells drilled, 12 produced oil, 4 produced gas, and 3 were dry.

Bronson, Elsmore, Savonburg, and Stark.—Prospecting in an irregular manner has been prosecuted to a limited extent in the eastern portion of the Iola quadrangle, particularly at Bronson, Elsmore, Savonburg, and Stark. In a few instances encouraging results were obtained, but thus far not sufficiently so to attract many prospectors away from the other areas.

PRODUCTION.

Oil.—The rapid rate of oil development in Kansas may be illustrated by the number of wells drilled. There were 725 producing oil wells at the end of June, 1903, not counting a number of unreported wells in some districts, and at the close of the year there were 1,596 producing wells, showing that a larger number of wells were drilled during the last half of 1903 than during all previous time. The subjoined table for the last half of the year covers the entire territory. It will be noticed that Chanute has the largest number, 549, and that Humboldt is second, with 339. In the territory around these two towns there is a total of 888, or considerably more than half of all reported.

KNAPP PUMPING STATION. STORAGE TANKS, AND LOADING RACKS, CHANUTE, KANS.

Wells drilled in Kansas, July to December, 1903.

District.	Wells producing July 1.	July.		August.		September.		October.		November.		December.		Total producing December 31, 1903.
		Completed.	Abandoned.	Completed.	Abandoned.	Completed.	Abandoned.	Completed.	Abandoned.	Completed.	Abandoned.	Completed.	Abandoned.	
Chanute	306	45	0	16	0	25	0	25	1	81	2	56	2	549
Humboldt	133	14	0	35	17	65	21	68	15	44	16	65	16	339
Neodesha	161	18	5	35	12	18	5	29	9	39	2	23	10	280
Peru	32	9	1	30	10	32	11	25	4	30	1	29	3	157
Independence	7	10	7	36	18	8	4	32	11	49	10	25	6	111
Cherryvale	18	4	1	10	1	....	....	....	....	18	1	2	0	49
Bartelsville [a]	34	7	1	8	1	13	3	5	0	12	2	6	1	77
Chelsea	33	....	....	....	....	....	....	....	....	....	....	....	5	28
Red Fork	1	2	....	....	....	....	....	....	....	3	....	....	....	6
Total	725	109	15	170	59	161	44	184	40	276	34	206	43	1,596

[a] Indian Territory.

The first oil produced in the Iola quadrangle was marketed in 1900, the oil being shipped in tank cars by Mr. Knapp. He continued shipments by rail throughout 1900, 1901, and 1902, and well into 1903, since which time his production is included in the pipe-line runs given in the monthly reports by the Prairie Oil and Gas Company. Figures for the total production of oil during 1900 or 1901, are not obtainable. It is probable, however, that the two years' combined production would be about 80,000 barrels. During 1902 the production was much greater, and rapidly increased throughout 1903. In 1902 the total production at Chanute was 165,336 barrels, about two-thirds of it being produced by Mr. Knapp. By the close of 1903, however, a number of other companies were regular producers. The subjoined table, showing the monthly production of Chanute and Humboldt, includes only pipe-line runs, to which should be added the oil shipped by rail and a small amount delivered to the wagon trade at Humboldt and sold to brick plants and other manufacturers.

Humboldt produced no oil in 1902, except from one well belonging to Mr. G. Z. Work. It is estimated that he sold at least 500 barrels to the wagon trade. In 1903 this same kind of trade was continued; by June shipments by rail began; and in the late summer the pipe lines were extended to the Humboldt field and the delivery of oil increased very rapidly, as shown by the table. At the close of 1903 probably fully one-third of all the wells in the Chanute-Humboldt district were still standing idle because pipe lines had not yet reached them. The pipe-line runs, therefore, are only an indication of what the total production would have been had market facilities been at hand.

Shipping oil by rail was begun at Moran late in 1903, but on account of poor shipping facilities only a small amount was marketed.

Other centers of smaller production, such as Erie, Shaw, Urbana, etc., either marketed no oil or had their production included with the pipe-line runs from Chanute. Nothing was marketed from any of these points until late in the year, and since then but little, because developments were scarcely beyond the prospecting stage.

Oil production of Iola quadrangle in 1903.

[Barrels.]

	Chanute.	Humboldt.		Chanute.	Humboldt.
January	25,811.40	....	July	34,481.65	578.00
February	26,291.60	....	August	67,822.28	....
March	12,812.41	....	September	82,850.23	1,743.50
April	9,965.90	....	October	75,141.57	6,079.70
May	46,033.57	431.00	November	74,175.44	6,743.22
June	34,494.05	144.43	December	74,182.64	6,868.22

By way of comparison, figures for the production of the entire State and adjoining points in the Indian Territory may be of interest.

Oil production of Kansas and adjoining Indian Territory in 1903.

[Barrels.]

	Chanute.	Humboldt.	Neodesha.	Peru.	Independence.	Cherryvale.	Indian Territory and Oklahoma.	Total.
January	25,811.40	....	7,440.38	2,975.06	....	1,154.87	7,146.76	44,528.47
February	26,291.60	....	6,328.29	2,845.79	....	965.15	5,697.34	42,128.17
March	12,812,41	....	7,586.06	3,773.14	....	1,205.76	4,126.93	29,504.30
April	9,965.90	....	6,706.38	3,036.34	....	425.56	7,033.88	27,168.06
May	46,033.57	431.00	9,305.74	2,634.15	....	1,083.23	4,277.78	63,765.47
June	34,494.05	144.43	6,836.69	2,133.98	....	922.94	8,239.81	52,771.90
July	34,481.65	578.00	6,390.50	2,133.64	....	735.21	16,102.74	60,421.74
August	67,822.28	....	10,838.35	3,272.90	....	1,353.24	10,490.69	93,777.46
September	82,850.23	1,743.50	9,900.52	4,930.83	5,759.94	705.29	8,821.85	114,712.16
October	75,141.57	6,079.70	12,528.69	2,952.19	15,297.01	1,683.06	14,315.49	127,997.71
November	74,175.44	6,743.22	19,821.00	11,987.89	34,776.54	3,634.35	24,613.01	175,751.45
December	74,182.64	6,868.22	28,986.48	21,898.78	50,876.54	10,843.76	34,831.69	238,488.11

Kansas oil wells are not very strong if compared with the more noted "gushers" of America. The wells in Neosho Valley, at Chanute or at Humboldt, had an average initial production of about 20 barrels, the strongest varying from 100 to 300 barrels daily capacity and the weakest from 1 to 3 barrels.

On the uplands to the east of the river, southeast of Humboldt and northeast of Chanute, the general character of the wells was much the same, except that a few were found which were stronger than any in the river valley. In the autumn of 1903 Martin Brothers brought in a well on the Lockhart land, sec. 13, T. 26 S., R. 18 E., which began flowing at about 1,000 barrels per day. A few weeks later the Minneapolis Oil and Gas Company brought in a well near by, likewise on the Lockhart land, which filled a 250-barrel tank in 250 minutes, a rate of about 1,440 barrels a day. These two had the greatest initial capacity of any thus far found in the State. Their rate of flow declined rapidly but remained at about 200 to 300 barrels per day for some months. In December, 1903, a few strong wells were brought in west of Chanute, just across the west boundary of the Iola quadrangle. They were much stronger than the average wells in Neosho Valley, but not equal to the wells on the Lockhart land.

Elsewhere in Kansas, outside of the Iola quadrangle, the oil wells are similar to those described. Southwest of Independence, in Montgomery County, near Bolton, during the summer and early autumn of 1903, a remarkable oil field was developed. The first good well was brought in on the Banks land, sec. 8, T. 33 N., R. 15 E. It was but a short time until a large number of wells were completed, averaging from 100 to 300 barrels per day, a great proportion of which were flowing wells. At present it seems that this is destined to be the greatest individual oil pool in the State. In the vicinity of Cherryvale good oil wells are becoming common, indicating that this also may soon be an oil center. Coffeyville also, late in 1903, became the center of active drilling operations.

Gas.—It is impossible to estimate with a high degree of accuracy the amount of gas produced in the Kansas fields. The historical sketch already given shows that gas was used in Iola as early as 1873, but pipes were not laid down for its general use until twenty years later, 1893. From that time to the present it has been used almost to the exclusion of other fuels for heating and lighting and for generating steam and producing furnace heat in the numerous manufacturing enterprises.

At Iola the manufacturing concerns are zinc smelters, brickkilns, Portland-cement factories, flouring mills, planing mills, and a number of small factories, such as are usually found in thriving young cities, including laundries, creameries, bakeries, etc. The zinc smelters of the entire Kansas gas field have produced 375,000 tons of spelter from gas furnaces, of which more than 300,000 tons were produced at Iola, Laharpe, and Gas. The gas used is the equivalent of about 2,000,000 tons of good soft coal. Kansas gas has burned about 650,000,000 brick, which would have required about 250,000 tons of coal. Of these brick about one-third were burned within the Iola quadrangle. The

Portland-cement factory at Iola during its operation has produced, in round numbers, 2,000,000 barrels of cement, consuming gas equivalent to 200,000 tons of coal.

The consumption of gas in the lesser factories and for domestic use has been great, aggregating more than that used in the factories. The rates charged are very low. Some data have been gathered on domestic consumption, but principally in terms of the value of gas rather than its quantity. It is probable that the entire Kansas field has produced gas having a value of very nearly $5,000,000. The rates charged by gas companies in different cities vary widely, but with few exceptions the modes of estimating values are the same. A charge of so much per month is made for each light and for each of the different kinds of stoves used. The most common price is 25 cents for a light and from $1.50 to $2.50 per month for a stove. A cooking stove for a residence is charged more than a warming stove, because it is usually larger and consumes more gas. Stoves in business houses, hotels, etc., are generally larger in size than those in residences, and consequently are charged a higher rate. At Chanute the gas is owned and sold by the city and prices are fixed by city ordinance. By the terms of the city ordinance which becomes effective February 2, 1903, gas charges were reduced one-half. Accordingly, the rates now charged are: Gas jet, 10 cents per month; heating stove, $1.50 per month; cooking, $1 to $1.50 per month. For all manufacturing purposes the gas is sold by the thousand cubic feet. A concern using 1,000 or less cubic feet per month is charged 20 cents; 2,000, 35 cents; 3,000, 50 cents; 8,000, $1; 10,000, $1.25; above 10,000 the rate is 5 cents for each additional thousand. At Erie all consumers use meter rates at 25 cents per thousand cubic feet burned.

The mode of burning gas is very objectionable from the standpoint of economy. All lights are allowed to burn continuously day and night excepting in extreme hot weather, when some of the lines are turned off in order to prevent throwing too much heat into the rooms.

If good meter rates had been established throughout the entire gas region it is probable that consumers might have used all the gas they needed for their comfort in lighting and heating without consuming more than from one-third to one-half of what has actually been burned.

Gas-producing territory.—The strength of gas wells varies from wells in which so little gas is found that they have no commercial value up to those which have a capacity of more than 10,000,000 cubic feet. The best wells developed thus far are in the Iola-Laharpe region. This territory extends about 9 miles east and west and 4 miles north and south, and has supplied much more gas than any other field in the State. Other fields are known which may prove to be as good, but they have not been drawn from so extensively. The original static pressure in the Iola area was about 325 pounds per square inch and the best wells generally had a flowing capacity of from 5,000,000 to 10,000,000 cubic feet per day. East of Laharpe and west of Moran is a territory not yet prospected. Moran is moderately supplied with gas, but the wells are weak compared with those at Laharpe and Iola.

Very little prospecting has been done in the extreme north end of the Iola quadrangle. A few wells to the north of Carlyle have proved of little value, and likewise to the northwest of Iola. Small gas wells have been found in the western part of Bourbon County, near Bronson. About 3 miles southwest of Iola, on the Culbertson land, there are two gas wells, one of which had an initial capacity of about 3,000,000 cubic feet per day. There is a large area between Iola and Humboldt hardly touched with the drill. What little prospecting has been done has not yet yielded very encouraging results, although too few wells have been drilled to permit one to form a judgment on the territory.

Gas has been found in comparative abundance in the vicinity of Humboldt. West of Humboldt, just beyond the limits of this quadrangle, are a number of gas wells which have a capacity of from 1,000,000 to 5,000,000 cubic feet per twenty-four hours. East and southeast of Humboldt a number of other wells of similar capacity have been found, but no gas territory distinct from the oil territory has yet been developed. This field joins the gas territory in the vicinity of Chanute, with no sharp boundary line between them.

In the vicinity of Chanute gas is abundant. The first gas wells were found in Neosho River Valley, east of the town, and on the low hills in the southeastern part of the town. In fact, so many wells were found in this latter place that the name Gas Ridge was applied to it some years ago. The territory here seems to be spotted, an occasional dry hole being sometimes found with producers on either side of it. The upland lying west of the town was abandoned at one time, as the few wells drilled proved to be failures. But later other wells were drilled a little farther west and also a mile or two to the south, which proved to be good producers. During 1902 and 1903 a number of good wells were drilled in the hills on the east side of the river from $2\frac{1}{2}$ to $3\frac{1}{2}$ miles east of Chanute. One particularly, which was completed in July, 1903, is almost as good a well as any in the State.

The territory lying to the south of Chanute in the southeast corner of the Iola quadrangle produced but little up to the close of 1903. A few light wells have been found, particularly near Urbana and south of the quadrangle toward Thayer and Galesburg, but the prospecting is not extensive enough to show the character of this part of the field.

In the vicinity of Erie small gas wells, with a daily flowage capacity of from 100,000 to 500,000 cubic feet, are found in comparative abundance. The first 35 holes drilled by the Erie Gas and Mineral Company obtained 14 gas wells, 7 oilers, and 14 failures. The gas is used satisfactorily to light and heat the town.

Outside of the places mentioned but little gas has yet been found. Considerable prospecting has been done at St. Paul, but with negative results. The first well at Walnut was drilled during the autumn of 1903, and was practically a failure, showing only a very small amount of gas. Other wells are to be drilled there, but what success they will have can not be foretold. Stark, Savonburg, Elsmore, and Bayard are similarly situated. A few wells have been drilled which produce small amounts of gas, but none sufficient to be of any considerable commercial importance. Possibly future prospecting will find larger quantities of gas.

UTILIZATION OF GAS IN ZINC SMELTING.

Attracted by the cheap fuel supplied from the numerous and strong gas wells, zinc-smelting companies years ago began erecting large smelters in the Kansas gas fields. To-day more than one-half of all the spelter produced in the United States is smelted by Kansas gas, and considerably more than half of this is produced by smelters located within the Iola quadrangle.

Development of the industry.—The first smelter erected was located at Iola and built by the Robert Lanyon's Sons Company. The company began producing spelter in December, 1896, but the plant was not brought into successful operation until the spring of 1897. A large stone building erected originally for a carriage manufactory was used for furnace rooms (Pl. VIII, *B*).

As this was the first plant to use natural gas for fuel, it was largely in the nature of an experiment, and its success was watched with great interest. It was recognized from the start that the difficulty in the use of gas, should any arise, would be in the proper distribution of heat through the furnaces. It was soon found that this could be accomplished readily by providing intakes of gas, arranged in different places, as experience showed desirable. The gas was mixed with the proper amount of air by specially contrived mixers, built on the general principles of the Bunsen-burner mixer, or those so widely employed in domestic consumption of gas. The success of the company led to the enlargement of the plant from time to time, until now it has 3,200 retorts. After about a year's trial the company built another large smelter at Laharpe, which has been enlarged from time to time until it has a capacity at present of 3,440 retorts.

The success achieved by the Robert Lanyon's Sons Company soon attracted the attention of others. During the summer of 1897, W. & J. Lanyon, who were operating zinc smelters in the coal fields at Pittsburg, Kans., erected a trial smelter of 1,800 retorts at Iola, and began the production of spelter late in December of the same year. Their

A. IOLA BRICK COMPANY'S PLANT NO. 1.

B. LANYON ZINC COMPANY'S SMELTER NO. 1.

plant was a success from the first and was gradually enlarged until at the present time it has 3,200 retorts.

These different plants were operated separately until March, 1899. Previous to this time the Palmer Oil Company of Ohio had obtained leases on a large acreage in the vicinity of Iola and Laharpe, and had obtained a number of strong gas wells, ranging in capacity from 5,000,000 to 10,000,000 cubic feet per day. A new company was formed which bought the gas property of the Palmer Oil Company and the zinc smelters of both the firms above named, receiving the property in March, 1899, since which time all of these smelters have been operated by one management, under the firm name of the Lanyon Zinc Company. Late in 1903 they had a total of 9,840 retorts in commission.

In 1902 the Lanyon Zinc Company erected rolling mills at Laharpe, which began operations on May 3, of that year. These mills were successful in their operation and were enlarged during the summer of 1903. At the present time they have a daily capacity of from 40,000 to 50,000 pounds of finished sheet zinc.

In 1899 the Prime Western Spelter Company erected a plant of 1,240 retorts and built a little town named Gas, situated 2 or 3 miles east of Iola. The plant was owned and controlled by Mr. L. T. McRea, Mr. J. A. Daly, and Dr. L. H. Callaway. About the same time the Cherokee-Lanyon Spelter Company, of Pittsburg, erected a plant at the same place, with a capacity of 1,240 retorts. These two plants were operated successfully from the start, but later were sold. Also, in 1898, Mr. George E. Nicholson, a zinc smelter from Nevada, Mo., built a plant of 1,200 retorts capacity about 1 mile east of Iola, which was operated successfully until bought out late in 1902, having been previously enlarged to a capacity of 1,640 retorts.

In 1902 the United Zinc and Chemical Company built a zinc smelter at Iola and a sulphuric-acid factory in connection with it. The plant was completed and began operations in March, 1903. The roasting furnace is so arranged that fumes from the burning gas do not come in contact with the ore, the heat entering the roasting chamber proper by being transmitted through a fire-clay floor on which the ore rests. Air is slowly drawn over the heated sulphide ore and oxidizes it, producing a sulphur dioxide (SO_2). By regulating the draft properly and by excluding the products of combustion from the gas, a greater concentration of sulphur-dioxide vapor can be obtained than from the ordinary calcining furnace. It can thus be passed directly into the leaden acid-generating chamber.

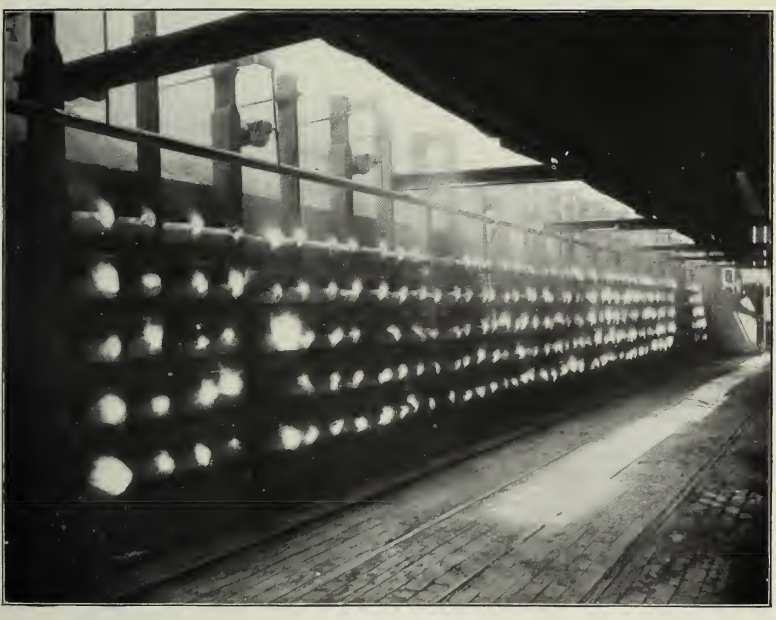
Late in 1902 a new company was organized as the New Jersey Zinc Company. It bought the plants of George E. Nicholson and the Prime Western Spelter Company, and has since operated them as one plant. During the last summer (1903) it has been enlarging its plant to almost double its original capacity. Also, in 1903, a Mr. Braun began building a small smelter at Laharpe, which is expected to go into commission near the end of the year.

On account of small values of gold and silver being found in zinc ores shipped from Colorado to Kansas furnaces, it was thought desirable to put up a trial furnace for the purpose of extracting such from the residue obtained from the retorts. In 1902 the Cherokee-Lanyon Company put up such a trial smelter. They shipped ores from Colorado and from Canada known to have small gold and silver values and extracted the precious metals from the retort residues. After a trial of about a year they abandoned the enterprise and permanently closed down their gold and silver smelter, finding that the expense was greater than the profit.

At the present time, summarizing the above data, there are in operation in the Iola quadrangle zinc smelters belonging to four different companies, with an aggregate capacity of about 17,000 retorts, not including the ones at Laharpe, which are not yet completed.

Method of smelting.—Zinc smelting with gas for fuel is conducted very similarly to zinc smelting with coal. Kansas smelters use almost exclusively ore from the Joplin-Galena mining district, which supplies zinc blende or zinc sulphide. Such ores, after being properly pulverized, are passed through the roasting or calcining furnace. Here the gas flame, mixed with an excess of air, comes in direct contact with the ore. The sulphur is gradually expelled as sulphur dioxide (SO_2), leaving the zinc in the form of zinc oxide (ZnO). From the calcining furnace the zinc oxide is taken to the retort or sublimation furnace, mixed with the proper amount of carbon, and placed in externally heated fire-clay retorts. These retorts, which are circular in cross section, 4 feet long and about 10 inches internal diameter, are arranged in the furnace so that they form a series of rows one upon the other, each retort being almost horizontal. The back or inner edge is closed in the making, but the outer end, which projects slightly through the wall of the furnace, is left open. After the charge is put into the retort a conical, hollow, fire-clay condenser is put into the open end of the retort. This gathers the vapor of metallic zinc volatilized by the heat of the furnace and holds it until enough has condensed to be drawn off. As this condenser is entirely outside the furnace its temperature is below the point of volatilization and above that of solidification and consequently serves the purpose well. The bulk of the carbon, which is mixed with the zinc oxide before it is put into the retorts, is in the form of coke made principally from slack coal obtained from the coal mines in Cherokee and Crawford counties. With this coke a small or varying amount of pulverized anthracite is used, to which is added a small proportion of pulverized bituminous coal, the whole charge being thoroughly mixed together. The retort is completely filled, after which an iron rod about 1 inch in diameter is

A. LANYON ZINC COMPANY'S SMELTER NO. 2.



B. BANK OF RETORTS SHOWING FLAMES AND ZINC FUMES ESCAPING FROM THE ENDS OF CONDENSERS.

forced into the top part of the charge through the entire length of the retort to make a little opening, along which the first volatile material may pass when the smelting has begun. The conical condenser is then inserted and the heat of the furnace soon causes chemical action to begin. The bituminous coal is added in order to produce a little volatilization early in the process. As the gas thus formed passes out of the retort it sets up to some extent an outward current. When the hot carbon reduces zinc oxide to metallic zinc the latter is immediately volatilized and driven over into the condenser. The carbon unites with the oxygen of zinc, producing a small amount of carbon dioxide (CO_2), but principally carbon monoxide (CO), a combustible gas that is set on fire at the outer end of the condenser. The small flame thus produced is colored slightly by traces of zinc vapor and other materials which may be in the ore, particularly cadmium, should any be present. The operator judges the temperature of the furnace and the rate of progress largely by the color of the flame, which varies from time to time with varying conditions of temperature and progress of reduction.

Production of spelter in 1902.—A retort, such as has been described above, produces from 23 to 25 pounds of metallic zinc for each charge, the amount varying slightly with the grade of the ore, but rarely exceeding these limits. It takes twenty-four hours to dispose of one charge, so the capacity of a furnace is obtained by allowing about 24 pounds of spelter per day for each retort. There are 17,000 retorts in the smelters in the Iola quadrangle at the present time. If no allowances were made for shut downs for repairs and other necessary stoppages, they would be able to produce nearly 75,000 tons of spelter per annum, an amount almost as great as the total State production for 1902. The difference between the figures obtained in this way and the actual amount of production is due to a number of causes, the principal one being that no furnace can be operated continuously year after year without repairs. It is quite unusual to find a large smelting plant with all of its furnaces in commission. Almost always one or more of them will be closed for repairs, or for some other temporary cause.

In 1902 the furnaces above described produced about 66,000 tons of spelter which, at the New York quotations, had a value of $6,201,600.

PHENOMENA OF GAS WELLS.

By George I. Adams.

When, in the operation of drilling, a reservoir of gas is encountered, its presence is immediately known by the fact that it flows from the well. As the drill goes deeper the volume of gas increases until it reaches the maximum production. In many instances the force of the gas assists in opening the reservoir by blowing out fragments of rock, and the well is said to "drill itself in." If the gas is under high pressure the force may be great enough to lift the drilling tools out of the well. The task of confining the gas is by no means an easy one. Sometimes the pressure causes the casing to rise out of the ground and it is necessary to secure it by means of anchors. If there are defects in the casing or valves they may break as a result of the pressure when an attempt is made to close the well. The sound made by the issuing gas is often deafening, and if the gas is ignited the flame causes a roar which may be heard for miles. To those who are at work around the well the effect is sometimes nauseating and otherwise disagreeable, and it is necessary to protect one's ears or permanent deafness may result.

The phenomena connected with the occurrence of natural gas, although now fairly well understood, are in a way mysterious and elusive. The first exploitation of gas began in the early seventies in Pennsylvania. Although but a short time has elapsed since then, the laws governing the utilization of gas are well understood by many operators. For the information of those who are interested in the occurrence of gas or who may wish to engage in prospecting, it is proposed here to review certain of the phenomena of gas wells.

For a proper understanding of the laws which govern the flow and pressure of gas it may be well first to explain the nature of a gaseous body. In a gas the molecules are separated beyond the limits of cohesive attraction so that they are free of all restriction upon one another. It is not known if there is a limit to the rarefaction of gases when they are unconfined; that is, at what distance the attraction of the molecules for each other would just balance the mutual repulsion. Gas may be said to fill a reservoir no matter how small the amount may be.

Natural gas, as it is commonly called, is a mixture of several gases, of which marsh gas (CH_4) is found in the Kansas product to constitute from 92 to 98 per cent. The following table[a] shows the composition of gas found at various localities in the Kansas field:

Composition of natural gas found in the Kansas field.

	Paola.	Osawatomie.	Iola.	Cherryvale.	Coffeyville.	Independence.	Neodosha.
Carbon dioxide	0.33	0.22	0.90	0.22	0.00	0.44	1.00
Olefiant gas, etc	.11	.22	.00	.00	.35	.67	.22
Oxygen	.45	Tr.	.45	.22	.12	Tr.	.65
Carbon monoxide	.57	1.33	1.23	1.16	.91	.33	.50
Marsh gas	95.20	97.63	89.56	92.46	96.41	95.28	90.56
Nitrogen	2.34	.60	7.76	5.94	2.21	2.28	7.07
Hydrogen	.00	.00	.00	.00	.00	.00	.00
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00

[a] Bailey, E. H. S., Kansas Univ. Quart., vol. 4, No. 1, July, 1895, p. 10.

Gas diffuses readily and when it issues from the well immediately becomes mixed with air. When it is used as fuel the necessary oxygen from the air is added to it by means of a mixer, which allows the diffusion of the air and gas to take place before it is burned. Gas is absorbed by water and oil, the amount absorbed depending upon the pressure and temperature. As an aid to the understanding of the relations of gas absorbed in a liquid ordinary carbonated water may be cited. When gases are once formed they are very stable and retain their condition excepting under very high pressure and low temperature. The degree of compression or density of gas is dependent upon the heat and pressure to which it is subjected. Gas expands against any constant pressure by one four hundred and ninety-first part of its volume for every degree Fahrenheit by which its temperature is raised. At a fixed temperature the volume of a body of gas decreases or increases at exactly the same rate that the pressure increases or decreases. The expansive force of gas is exerted in all directions and the pressure on confined bodies is transmitted undiminished.

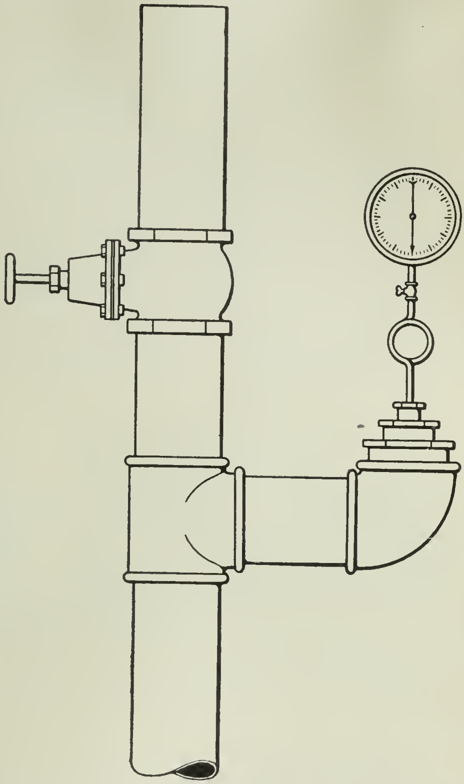


FIG. 4.—Spring gage attached for measuring static pressure.

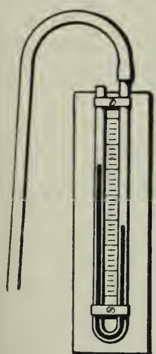


FIG. 5.—U-shaped gage with flexible hose for attachment in measuring gas pressures.

Static or closed pressure.—A body of gas confined within the earth, if not subjected to geologic changes, remains in a quiescent state until reached by the drill. A well forms an artificial extension of the body of gas and affords an opportunity to measure its degree of condensation. When the pressure in a closed well is moderately high it may be measured by connecting a spring gage with the casing (fig. 4). The gage records the pressure in the same way as does a steam gage on a boiler. If the pressure is small a U-shaped tube (fig. 5), containing mercury, water, or other liquid, may be connected with the casing and the pressure registered by the height to which the column of liquid rises. The U-shaped gage, because of the nature of the instrument, can be used only for low pressures.

While a measurement so taken is commonly stated to be the pressure of the gas in the well, the fact should not be lost sight of that it is the measure of the pressure exerted by the gas on all parts of the reservoir of which the well is an artificial prolongation. The static pressure recorded when a well is first brought in is commonly spoken of as its initial pressure. Any variations which are recorded in subsequent measurements are found to be lower. For example, if, after a well is measured, it is allowed to blow off and is then suddenly closed the pressure on the gage will be lower than it was before the valve was opened, the reduction being caused by the friction encountered in flowing. However, the index on the dial of the gage will gradually change its position, indicating a higher pressure and in the course of a short period will record the same pressure as was just previously note '.

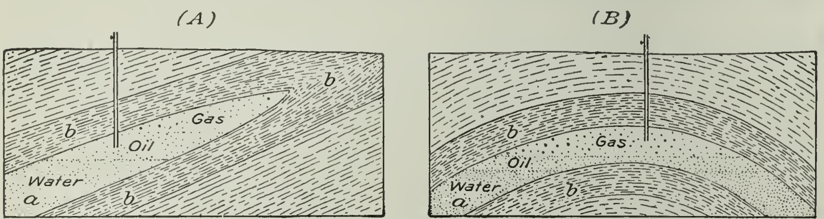


FIG. 6.—Types of oil and gas reservoirs.

A, inclined bed of sandstone (*a*) sealed in by shales (*b*), but somewhere in communication with water under hydrostatic pressure.

B, sandstone bed (*a*) interstratified with impervious beds (*b*) and forming an arch or anticline, and somewhere in connection with water under hydrostatic pressure.

In the Kansas field a pressure of 325 pounds to the square inch is not unusual. Many wells show a lower pressure, and some are reported to reach 600 pounds. The force of the gas issuing from a well as computed in horsepower reaches a surprising figure, being so great that the gas may be turned directly into the cylinder of a steam engine and its expansion utilized as a source of power. High pressures in the field are desirable since they enable the gas to be conveyed long distances through ramifying pipe lines, where the friction which must be overcome is a serious element.

After a well has produced for a considerable period of time the pressure will be found to have fallen off. This is the history of the wells in all fields. The fact may be taken as an indication that the exhausting of the gas changes the relations in the reservoir. The gas confined within the earth occupies the interstitial spaces in sandstones and porous rocks. A gas reservoir accordingly is a complex series of openings. Its limits are the impervious rocks which inclose its upper surface and the water or oil which lies below it. The two types of reservoir considered from the standpoint of the structure of the rocks are shown in the accompanying figure (fig. 6).

The degree of density of gas under hydrostatic conditions in a reservoir depends upon the pressure exerted upon it by the oil and the water. The amount of this pressure is due to the hydrostatic head. If the place of intake of the water is known and it is assumed that the water-bearing stratum is completely saturated, the pressure of the gas can be computed by measuring the height of the column of water acting on it. The observed pressure in closed wells is found to check closely with the results obtained where these factors are known. A simple example illustrating the hydrostatic head is shown in the accompanying diagram of an artesian well (fig. 7).

The fact that a well shows a high pressure is evidence of the relative density of the body of gas, but it does not indicate the capacity of the reservoir. If the hydrostatic conditions are perfect the pressure of the gas will be very nearly maintained throughout the life of the well whether the reservoir is large or small, the difference in pressure being due simply to change in the level of the water.

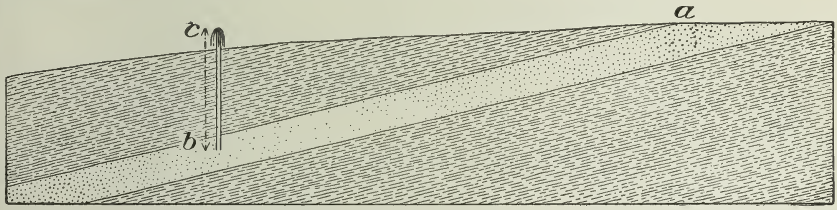


FIG. 7.—Diagram of an artesian well: *a*, point of intake; *b-c*, height of column of water exerting hydrostatic pressure at *b*.

As the gas in the reservoir is reduced in quantity by flowing out of the well the water or oil limiting its lower surface rises. The amount of decrease in pressure may be measured by subtracting the weight of a column of water or oil having a height equal to the difference in its original and subsequent levels. Inasmuch as the movement of water in the earth's crust is much retarded by friction, and in some cases may be modified by changes in porosity of the strata owing to cementation of the rocks after the gas has accumulated, the observations on wells show variations from ideal conditions.

Dynamic or open-flow pressure.—In flowing through a well casing gas encounters the resistance of friction, which is relatively large in small pipes. The dynamic or open-flow pressure at the mouth of the well is equal to the static or closed pressure minus the friction. As will appear later in this discussion, the velocity of the flow bears a fixed relation to this pressure.

In all measurements under ordinary conditions atmospheric pressure is a factor. It may, however, be neglected, since the apparatus used is so constructed that atmospheric pressure on the gas is balanced by atmospheric pressure on the opposite side of the diaphragm in spring gages or of the column of liquid in U-shaped tube gages. The measurements recorded are accordingly for gas under pressure of one atmosphere. The weight of a column of air at sea level is about 14.7 pounds per square inch. Corrections for altitude may be made by reference to barometric readings, but in ordinary work are usually neglected. In accurate measurements of volume corrections for temperature are made. The volume of flowing gas is computed at 40° F., and for gas in a reservoir a temperature of 50° F. is taken as the standard. The specific gravity of natural gas is about six-tenths, air being considered as one. Corrections for exact specific gravity of gas may also be made if desirable.

The volume of gas flowing from a well or through a pipe is expressed

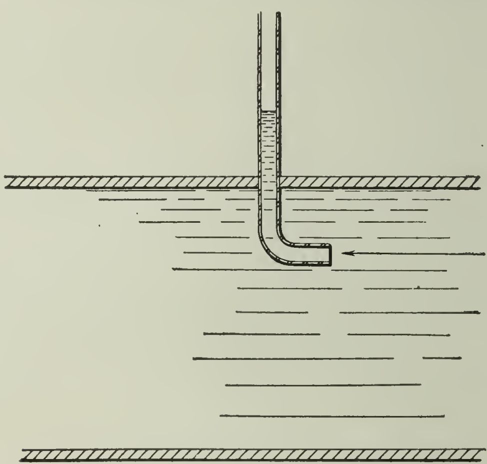


FIG. 8.—Simple form of Pitot tube.

in cubic feet. When a measurement is made, the size of the inside diameter of the pipe should be stated. This is because the carrying capacity of pipes varies as a square root of the fifth power (that is, as a 2.5 power) of the diameter, and although there is an increase in the velocity of flow with a decrease in size of the pipe, this does not entirely compensate for the increased friction. The tables commonly used in computing volumes are apt to be misleading if this fact is not borne in mind, for in measuring the volume, the well tubing is usually reduced to a 2-inch nipple. If it is desirable to determine the full capacity of a well, measurements should be made in the tubing.

As a result of friction currents the velocity of flow is not uniform over all parts of the area of a well opening. Experiments have shown that the points of mean velocity are about midway between the center and the circumference of the casing. In measuring the volume of gas issuing, it is necessary to determine its velocity and compute the amount for the size of the pipe. For measuring the velocity, the Pitot tube is employed.[a]

The simplest form of this instrument is shown in fig. 8, in which the velocity of flowing water is shown to cause a rise of head in the tube. In accordance with the laws of physics (and as may be found by experiments) the height of the column is doubled when the velocity is squared.

The velocity of gas flowing from a well may also be determined by means of a spring gage in accordance with the following facts: The pressure required to drive a unit amount of gas through an opening must be increased fourfold for twice the amount of gas, since double the amount must pass in a given time and the unit amount must move with double the speed. Inasmuch as the density of the gas at the level of the casing is constant, being that produced by atmospheric pressure, the relative velocity may be determined by measuring the pressure, and is found to be doubled when the pressure is four times as great. The method of using a spring gage is illustrated in fig. 9.

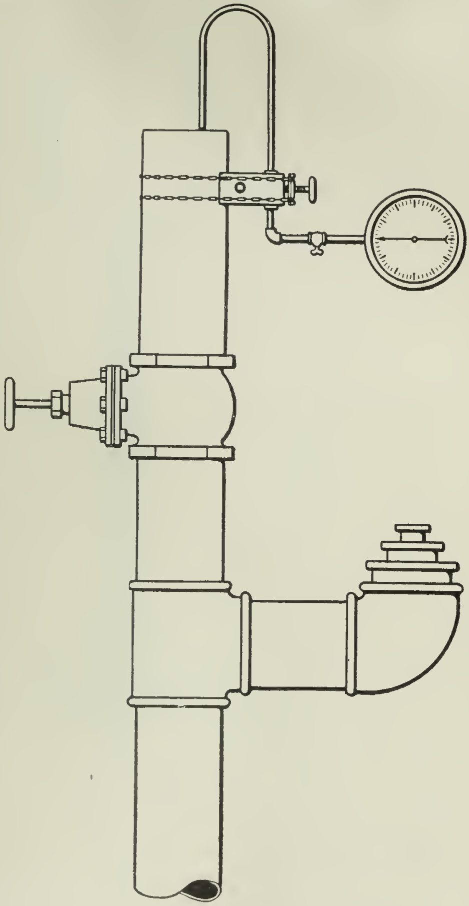


FIG. 9.—Pitot tube and spring gage attached for measuring veloeity of gas issuing from a well.

Actual measurements may be made by means of volumetric meters. Such will furnish the basis for computing volumes by means of velocity and pressure, and will show that they check very closely with the volumes computed from observations made with gages. A table, known as the Robinson table, in common use for computing the discharge of gas wells, is inserted here for reference.

[a]This instrument takes its name from the inventor, Pitot, who made it known to the French Academy of Sciences in 1732. Its adaptability for measuring the flow of gas was demonstrated by Prof. S. W. Robinson of the Ohio State University, who, by careful experimental tests, proved that the results obtained by it agree with the theoretical ones, while the instrument may be either fine or rude in construction. See Van Nostrand's Engineering Magazine, vol. 18; Geol. Survey Ohio, vol. 6, 1888; and First Ann. Rept. Geol. Survey, Ohio, 1890.

Pressure and flow in pipes.—The volume of gas flowing through a pipe at any point may be measured by determining the velocity and internal pressure of the gas. The Pitot tube is adapted to this use, and can be inserted into the flowing gas at the point of average velocity by drilling a hole in the pipe and making tight connection (fig. 10). The reading on the gage will be the pressure due to velocity plus the internal pressure. The internal pressure, which must be substracted

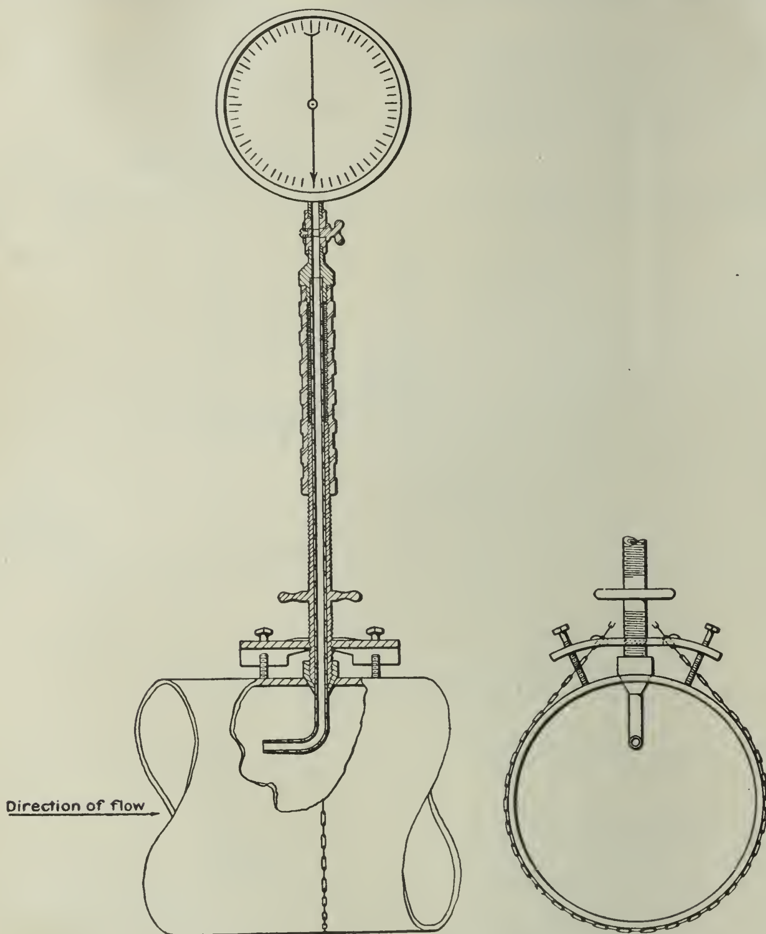


FIG. 10.—Pitot tube and spring gage, attached for measuring velocity of flow of gas in a pipe.

in order to determine the pressure due to velocity, can be measured by connecting a spring gage or U-shaped tube in a similar manner, but so arranged that it records only the pressure transmitted laterally (see fig. 11). If the apparatus is arranged as in fig. 12, the reading on the gage will be the difference of the two, or the pressure due to velocity of flow. This form of instrument is known as the Robinson instrument. It may be used with spring gages, or, by detaching the

3,000	11,844,000	14,990,000	17,055,000
9,000	12,246,000	15,499,000	17,634,000
5,000	12,648,000	16,008,000	18,213,000
1,000	13,050,000	16,517,000	18,792,000
5,000	13,462,000	17,038,000	19,386,000
9,000	14,147,000	17,905,000	20,371,000
3,000	14,372,000	18,645,000	21,214,000
5,000	15,833,000	20,040,000	22,800,000
9,000	16,875,000	21,357,000	24,300,000
9,000	17,839,000	22,577,000	25,688,000
0,000	18,716,000	23,977,000	26,951,000
2,000	19,484,000	24,659,000	28,057,000
4,000	21,129,000	26,741,000	30,425,000
9,000	22,555,000	28,894,000	32,478,000
5,000	23,870,000	30,211,000	34,373,000
3,000	24,967,000	31,599,000	35,952,000
3,000	25,918,000	32,802,000	37,321,000
8,000	26,800,000	33,919,000	38,592,000
4,000	27,672,000	35,023,000	39,848,000
6,000	28,440,000	36,000,000	40,953,000

TABLE 1.—*Cubic feet of gas discharged by gas well per day.*

[Cubic feet of gas reckoned at 32° F., discharged by well per day of 24 hours of continuous uniform flow, by Pitot-meter measurement, the specific gravity[a] of the gas being here taken at 0.6 (air=1), and the temperature of the flowing gas at well mouth being taken at 32° F. Cubic feet per day, reckoned at 32° F., given by this table, may be regarded as a quantity of gas in a gas holder at air pressure, and at the temperature of 32° F., for the "temperature of storage." For 50° temperature of storage, and for other temperatures of flowing gas, correct the cubic feet of gas obtained from this table by aid of note at bottom of table.]

Observed pressure by mercury gage.	Observed pressure by water gage.	Observed pressure by pressure gage.	Cubic feet of gas discharged.										
			1 in. diameter.	1¼ in. diameter.	2 in. diameter.	2½ in. diameter.	3 in. diameter.	3½ in. diameter.	4 in. diameter.	4½ in. diameter.	5 in. diameter.	5½ in. diameter.	6 in. diameter.
Inches.	*Inches.*	*Lbs. per sq. in.*											
	0.10	0.0036	12,390	27,880	49,556	77,440	111,510	151,780	198,220	250,890	309,750	392,000	446,040
	.20	.0073	17,560	39,510	70,260	109,750	158,040	215,110	281,040	355,590	439,000	555,910	632,160
	.30	.0109	21,480	48,330	85,940	134,250	193,320	263,130	343,760	434,970	537,000	679,630	773,280
	.50	.0182	27,720	62,370	110,880	173,250	249,480	339,570	443,520	561,330	693,000	877,080	997,920
0.05	.70	.0254	32,820	73,840	131,260	205,100	295,380	402,000	525,050	664,610	820,400	1,038,500	1,181,520
.07	1.00	.0364	39,210	88,230	156,830	245,100	352,890	480,400	627,310	794,030	980,400	1,240,700	1,411,600
.11	1.50	.0545	48,030	108,070	192,120	300,200	432,270	588,400	768,480	972,600	1,200,800	1,517,900	1,729,100
.15	2.00	.0727	55,340	124,520	221,360	345,900	498,060	677,960	885,440	1,120,600	1,383,600	1,751,000	1,992,200
.22	3.00	.1090	67,910	152,800	271,630	424,500	611,190	832,020	1,086,510	1,375,200	1,698,000	2,148,800	2,444,800
.29	4.00	.1450	78,410	176,420	313,660	490,100	705,690	960,600	1,254,620	1,587,800	1,960,400	2,480,900	2,822,800
.37	5.00	.1820	87,670	197,260	350,670	548,400	789,030	1,074,860	1,402,670	1,775,310	2,193,600	2,733,900	3,156,100
.52	7.00	.2540	103,500	232,880	414,000	646,900	931,500	1,267,900	1,656,000	2,095,900	2,587,600	3,274,800	3,726,000
.74	10.00	.3636	123,000	276,750	492,000	768,800	1,107,000	1,506,700	1,968,000	2,490,800	3,075,000	3,890,900	4,428,000
1.02	13.75	.5000	146,220	328,990	584,880	913,880	1,316,000	1,791,200	2,339,500	2,760,900	3,655,500	4,626,500	5,864,000
1.52	20.62	.7500	175,350	394,540	701,400	1,096,000	1,578,150	2,148,160	2,805,600	3,550,900	4,384,000	5,548,200	6,312,600
2.03	27.50	1.0000	201,800	454,010	807,200	1,261,200	1,816,050	2,471,900	3,228,500	4,086,100	5,044,600	6,384,600	7,264,200
3.05	41.25	1.5000	247,840	557,650	991,370	1,549,000	2,231,000	3,036,000	3,965,000	5,019,000	6,196,000	7,842,000	8,922,000
4.07	55.00	2.0000	285,130	641,540	1,140,500	1,782,000	2,566,200	3,493,000	4,562,000	5,774,000	7,128,000	8,921,000	10,265,000
5.08	68.75	2.5000	316,500	712,130	1,266,000	1,978,000	2,848,500	3,877,000	5,064,000	6,409,000	7,913,000	10,014,000	11,394,000
6.10	82.50	3.0000	344,350	774,780	1,377,400	2,152,000	3,099,100	4,218,000	5,510,000	6,973,000	8,609,000	10,895,000	12,397,000
7.12	96.25	3.5000	370,000	832,500	1,480,000	2,313,000	3,330,000	4,532,500	5,920,000	7,493,000	9,250,000	11,707,000	13,320,000
8.13	110.00	4.0000	393,000	884,250	1,572,000	2,456,000	3,537,000	4,814,200	6,288,000	7,958,000	9,825,000	12,435,000	14,148,000
8.15		4.5000	415,270	934,350	1,661,100	2,595,000	3,737,400	5,087,000	6,644,000	8,409,000	10,382,000	13,139,000	14,950,000
10.17		5.0000	436,200	981,450	1,744,800	2,726,000	3,925,800	5,343,000	6,979,000	8,833,000	10,905,000	13,802,000	15,703,000
11.18		5.5000	456,200	1,026,500	1,824,800	2,851,300	4,105,900	5,589,000	7,299,000	9,238,000	11,405,000	14,435,000	16,423,000
12.20		6.0000	473,750	1,065,900	1,895,000	2,961,000	4,264,000	5,803,000	7,580,000	9,593,000	11,844,000	14,990,000	17,055,000
13.21		6.5000	489,840	1,102,100	1,959,400	3,062,000	4,409,000	6,001,000	7,837,000	9,919,000	12,246,000	15,499,000	17,634,000
14.23		7.0000	505,920	1,138,300	2,023,700	3,162,000	4,553,300	6,198,000	8,095,000	10,245,000	12,648,000	16,008,000	18,213,000
15.25		7.5000	522,010	1,174,500	2,088,000	3,263,000	4,698,000	6,395,000	8,353,000	10,571,000	13,050,000	16,517,000	18,792,000
16.26		8.0000	538,500	1,211,600	2,154,000	3,366,000	4,846,000	6,597,000	8,616,000	10,905,000	13,462,000	17,038,000	19,386,000
18.30		9.0000	565,970	1,273,200	2,263,000	3,537,000	5,093,000	6,932,000	9,054,000	11,459,000	14,147,000	17,905,000	20,371,000
20.33		10.0000	589,270	1,325,900	2,357,100	3,683,000	5,303,000	7,219,000	9,428,000	11,933,000	14,372,000	18,645,000	21,214,000
24.39		12.0000	633,340	1,425,000	2,533,300	3,958,000	5,700,000	7,758,000	10,133,000	12,825,000	15,833,000	20,040,000	22,800,000
28.46		14.0000	675,000	1,508,800	2,700,000	4,219,000	6,075,000	8,269,000	10,800,000	13,669,000	16,875,000	21,357,000	24,300,000
32.53		16.0000	713,550	1,605,500	2,854,200	4,459,700	6,422,000	8,741,000	11,415,000	14,449,000	17,839,000	22,577,000	25,688,000
36.60		18.0000	748,650	1,684,500	2,994,600	4,679,000	6,738,000	9,151,000	11,978,000	15,160,000	18,716,000	23,977,000	26,951,000
40.66		20.0000	779,350	1,753,500	3,117,400	4,871,000	7,014,000	9,546,000	12,470,000	15,782,000	19,484,000	24,659,000	28,057,000
50.81		25.0000	845,150	1,901,600	3,381,000	5,282,000	7,606,000	10,353,000	13,522,000	17,114,000	21,129,000	26,741,000	30,425,000
61.00		30.0000	902,180	2,029,900	3,609,000	5,639,000	8,120,000	11,054,000	14,435,000	18,269,000	22,555,000	28,894,000	32,478,000
71.16		35.0000	954,820	2,148,300	3,819,000	5,968,000	8,593,000	11,697,000	15,277,000	19,335,000	23,870,000	30,211,000	34,373,000
		40.0000	998,680	2,247,000	3,995,000	6,242,000	8,988,000	12,234,000	15,979,000	20,223,000	24,967,000	31,599,000	35,952,000
		45.0000	1,036,700	2,332,600	4,147,000	6,479,000	9,330,000	12,700,000	16,587,000	20,993,000	25,918,000	32,802,000	37,321,000
		50.0000	1,072,000	2,412,000	4,288,000	6,700,000	9,648,000	13,132,000	17,152,000	21,708,000	26,800,000	33,919,000	38,592,000
		55.0000	1,106,880	2,495,000	4,428,000	6,918,000	9,962,000	13,539,000	17,710,000	22,454,000	27,672,000	35,023,000	39,848,000
		60.0000	1,137,600	2,559,600	4,550,000	7,110,000	10,238,000	13,935,000	18,101,000	23,036,000	28,440,000	36,000,000	40,953,000

[a] To change results by this table to those for any other specific gravity of gas than 0.6, multiply by $\sqrt{\frac{0.6}{\text{Sp. gr. gas.}}}$

NOTE.—For temperature of flowing gas where observed of 30°, 40°, 50°, 60° F., add 4, 3, 2, 1 per cent., respectively.
Should 98 per cent alcohol be used in gage, multiply the readings by 0.8 to reduce to water value.
Should 0.75 specific gravity kerosene be used in gage, multiply the readings by 0.75 to reduce to water value.

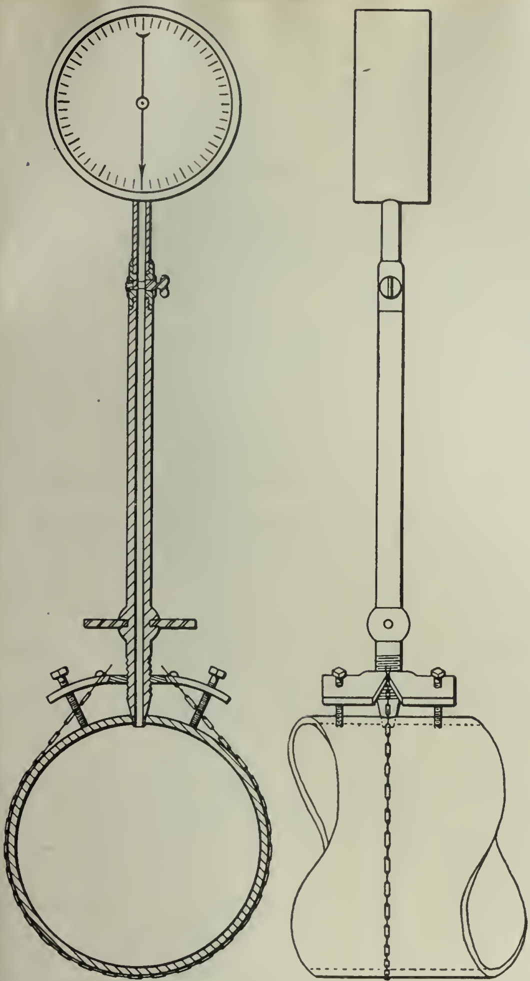


FIG. 11.—Spring gage attached for measuring internal pressure of gas flowing in a pipe.

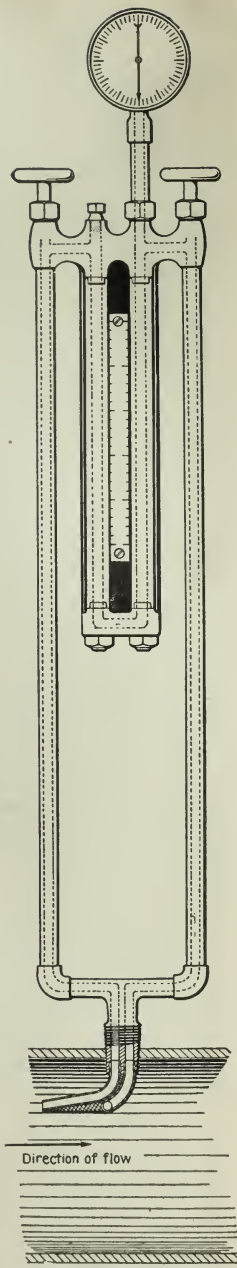


FIG. 12.—Robinson instrument for measuring velocity and pressure of gas flowing in pipes.

spring gage and filling the U-shaped tube in the center of the instrument, may be used as a mercury or water gage. Separate readings of static and flow pressure may be made by closing the valves at the top of the instrument. Tables for avoiding the necessity of computation have been prepared by Professor Robinson for various sized pipes. Corrections may be made in these for difference in specific gravity and temperature.

Minute pressure, or measurement of volume by number of condensations.—If gas is allowed to flow into a reservoir of known capacity the

TABLE II (FOR USE WITH PITOT METER).—*Cubic feet of gas, per hour of uniform flow, discharged through a 1-inch pipe line, the measured volume being as at air pressure and with specific gravity of 0.6* [a]; *the temperature of storage being 50° F., and of flowing gas 40° F.*

Pitot meter manometer.			0	0.63	1.26	1.91	2.57	3.82	5.07	7.65	10.11	20.22	30.37	40.41	50.55	60.63	Static pressure of gas flowing in the pipe line, in inches of column of mercury gage.														
			0	8.60	17.20	26.00	35.00	52.00	69.00	104.00	138.00	275.00	413.00	550.00	688.00	825.00	Static pressure of gas flowing in the pipe line, in inches of column of water gage.														
			0	5.00	10.00	15.00	20.00	30.00	40.00	60.00	80.00	160.00	240.00	320.00	400.00	480.00	560	640	800	960	1,120	1,280	1,600 = Ounces of gage pressure of gas flowing in pipe line.								
Mercury reading.	Water reading.	Alcohol reading.	0	.31	.625	.94	1.25	1.875	2.50	3.75	5.00	10.00	15.00	20.00	25.00	30.00	35	40	50	60	70	80	100	120	140	160	180	200	220	240	260 pounds.
Inches.	*Inches.*	*Inches.*																													
....	0.02	0.025	239	242	244	247	249	254	259	268	276	309	339	366	392	415	437	458	498	535	569	602	663	717	768	816	861	905	946	985	1,024
....	.04	.050	323	342	345	349	353	359	366	379	391	437	479	517	552	586	618	648	704	756	806	852	937	1,014	1,088	1,154	1,219	1,280	1,338	1,394	1,447
....	.06	.075	415	419	423	428	432	440	448	464	479	535	586	633	680	718	757	794	863	927	987	1,063	1,148	1,242	1,338	1,414	1,492	1,567	1,638	1,707	1,773
....	.08	.100	479	484	488	493	498	508	517	535	553	618	677	731	782	829	874	916	996	1,070	1,139	1,204	1,325	1,434	1,539	1,633	1,724	1,809	1,892	1,971	2,047
....	.10	.125	535	541	546	552	557	568	578	598	618	691	757	818	874	927	977	1,025	1,114	1,196	1,274	1,347	1,482	1,603	1,717	1,825	1,927	2,024	2,115	2,204	2,288
....	.15	.187	655	662	669	676	690	695	708	733	757	846	927	1,001	1,070	1,135	1,196	1,255	1,364	1,466	1,560	1,649	1,814	1,963	2,104	2,236	2,360	2,478	2,590	2,699	2,803
....	.20	.250	757	765	772	780	787	802	818	846	874	977	1,070	1,156	1,236	1,311	1,381	1,449	1,576	1,692	1,802	1,904	2,096	2,267	2,430	2,582	2,725	2,861	2,991	3,116	3,236
....	.25	.312	846	855	863	872	880	897	914	946	977	1,093	1,197	1,292	1,382	1,465	1,544	1,620	1,761	1,892	2,013	2,129	2,343	2,535	2,718	2,886	3,047	3,199	3,344	3,484	3,618
....	.30	.375	927	936	946	955	965	983	1,001	1,036	1,070	1,197	1,310	1,461	1,514	1,605	1,692	1,775	1,929	2,072	2,206	2,332	2,566	2,777	2,975	3,162	3,337	3,505	3,664	3,816	3,963
....	.40	.500	1,070	1,081	1,092	1,103	1,114	1,135	1,156	1,201	1,235	1,382	1,513	1,635	1,748	1,854	1,954	2,049	2,228	2,393	2,548	2,693	2,963	3,028	3,436	3,651	3,854	4,047	4,230	4,407	4,577
....	.50	.625	1,196	1,209	1,223	1,233	1,242	1,269	1,292	1,338	1,381	1,545	1,692	1,828	1,954	2,072	2,184	2,291	2,490	2,675	2,848	3,011	3,313	3,585	3,844	4,082	4,309	4,524	4,730	4,927	5,117
....	.60	.750	1,311	1,323	1,338	1,351	1,364	1,390	1,461	1,468	1,513	1,692	1,854	2,002	2,140	2,270	2,393	2,510	2,728	2,930	3,120	3,298	3,630	3,928	4,208	4,472	4,720	4,956	5,181	5,398	5,605
....	.80	1.000	1,513	1,530	1,546	1,560	1,575	1,605	1,635	1,692	1,747	1,954	2,140	2,312	2,471	2,621	2,763	2,898	3,150	3,384	3,602	3,808	4,191	4,535	4,860	5,163	5,150	5,723	5,983	6,232	6,473
....	1.00	1.250	1,692	1,709	1,727	1,744	1,761	1,795	1,828	1,892	1,954	2,185	2,393	2,585	2,763	2,931	3,089	3,240	3,522	3,782	4,028	4,256	4,686	5,070	5,433	5,773	6,094	6,398	6,689	6,968	7,236
....	1.20	1.500	1,853	1,871	1,875	1,911	1,929	1,966	2,002	2,076	2,140	2,393	2,621	2,831	3,027	3,210	3,384	3,549	3,858	4,144	4,412	4,664	5,133	5,554	5,951	6,323	6,675	7,009	7,328	7,633	7,927
0.10	1.40	1.750	2,002	2,025	2,123	2,064	2,084	2,123	2,162	2,240	2,312	2,585	2,831	3,058	3,269	3,468	3,699	3,834	4,168	4,476	4,768	5,036	5,544	5,999	6,128	6,830	7,210	7,570	7,915	8,245	8,562
.12	1.60	2.000	2,140	2,168	2,196	2,206	2,228	2,270	2,312	2,393	2,471	2,763	3,027	3,269	3,495	3,707	3,908	4,100	4,456	4,781	5,096	5,384	5,926	6,413	6,879	7,302	7,708	8,093	8,162	8,814	9,154
.13	1.80	2.250	2,270	2,291	2,324	2,340	2,363	2,408	2,454	2,538	2,621	2,931	3,210	3,420	3,707	3,932	4,144	4,348	4,724	5,076	5,404	5,700	6,286	6,802	7,289	7,744	8,175	8,584	8,974	9,348	9,709
.15	2.00	2.500	2,393	2,409	2,456	2,466	2,490	2,538	2,585	2,676	2,763	3,089	3,384	3,656	3,908	4,144	4,368	4,584	4,980	5,352	5,696	6,020	6,626	7,170	7,683	8,164	8,618	9,049	9,460	9,854	10,236
.18	2.50	3.120	2,675	2,702	2,740	2,758	2,784	2,837	2,890	2,975	3,089	3,455	3,785	4,087	4,368	4,636	4,884	5,118	5,568	5,980	6,368	6,732	7,408	8,016	8,595	9,127	9,634	10,120	10,580	11,016	11,444
.22	3.00	3.750	2,931	2,958	3,000	3,021	3,050	3,108	3,166	3,277	3,384	3,784	4,144	4,477	4,784	5,184	5,352	5,612	6,100	6,552	6,976	7,376	8,115	8,781	9,409	9,998	10,554	11,084	11,587	12,070	12,532
.29	4.00	5.000	3,384	3,419	3,459	3,487	3,522	3,589	3,655	3,798	3,907	4,369	4,786	5,169	5,524	5,860	6,176	6,480	7,044	7,568	8,056	8,516	9,370	10,143	10,865	11,541	12,188	12,797	13,380	13,935	14,470
.37	5.00	6.250	3,784	3,822	3,867	3,900	3,938	4,031	4,087	4,230	4,369	4,885	5,351	5,779	6,176	6,552	6,908	7,244	7,876	8,160	9,008	9,520	10,474	11,340	12,155	12,908	13,515	14,314	14,964	15,580	16,180
.44	6.00	7.500	4,145	4,185	4,237	4,272	4,313	4,396	4,477	4,643	4,786	5,351	5,861	6,331	6,768	7,180	7,568	7,936	8,628	9,268	9,868	10,428	11,477	12,120	13,304	14,140	14,925	15,674	16,380	17,070	17,730
.59	8.00	10.000	4,786	4,838	4,886	4,933	4,918	5,076	5,169	5,351	5,526	6,179	6,796	7,310	7,816	8,288	8,736	9,164	9,964	10,700	11,392	12,044	13,252	14,340	15,367	16,326	17,240	18,097	18,920	19,710	20,470
.74	10.00	12.500	5,357	5,407	5,461	5,520	5,569	5,677	5,780	5,980	6,178	6,908	7,567	8,173	8,736	9,268	9,768	10,248	11,136	11,964	12,740	13,468	14,816	16,030	17,180	18,255	19,270	20,240	21,150	22,035	22,880
.88	12.00	15.000	5,861	5,917	5,980	6,042	6,100	6,216	6,331	6,565	6,768	7,567	8,289	8,953	9,571	10,153	10,701	11,226	12,201	13,108	13,953	14,750	16,230	17,560	18,820	19,996	21,108	22,167	23,174	24,138	25,066
1.10	15.00	18.750	6,553	6,634	6,714	6,755	6,900	6,950	7,079	7,327	7,567	8,461	9,268	10,010	10,674	11,567	11,963	12,580	13,643	14,652	14,970	16,490	18,145	19,635	21,040	22,357	23,600	24,780	25,900	26,990	28,037
1.47	20.00	25.000	7,567	7,616	7,753	7,799	7,878	8,025	8,174	8,461	8,737	9,770	10,700	11,560	12,359	13,107	13,813	14,490	15,751	16,920	18,015	19,042	20,950	22,670	24,295	25,816	27,250	28,610	29,915	31,160	32,360
1.84	25.00	31.250	8,461	8,514	8,661	8,721	8,802	8,972	9,138	9,460	9,768	10,925	11,970	12,920	13,815	14,651	15,445	16,200	17,611	18,919	20,140	21,290	23,427	25,350	27,183	28,861	30,470	31,990	33,460	34,840	36,180
2.21	30.00	37.500	9,268	9,354	9,488	9,558	9,645	9,829	10,010	10,365	10,700	11,965	13,105	14,160	15,135	16,053	16,921	17,750	19,292	20,721	22,061	23,320	25,660	27,770	29,755	31,618	33,370	35,050	36,640	38,160	39,630
2.94	40.00	50.000	10,701	10,815	10,940	11,030	11,142	11,350	11,560	12,010	12,355	13,820	15,130	16,350	17,477	18,534	19,537	20,492	22,275	23,930	25,475	26,930	29,630	30,278	34,360	36,513	38,540	40,470	42,300	44,070	45,770
3.68	50.00	62.500	11,965	12,090	12,230	12,330	12,450	12,690	12,950	13,380	13,814	15,450	16,920	18,280	19,537	20,720	21,511	22,910	24,905	26,753	28,483	30,110	33,130	35,850	38,440	40,820	43,090	45,240	47,320	49,270	51,170
4.42	60.00	75.500	13,106	13,233	13,400	13,510	13,640	13,900	14,160	14,680	15,130	16,920	18,535	20,020	21,403	22,700	23,928	25,098	27,285	29,305	31,201	32,980	36,300	39,280	42,080	44,720	47,200	49,560	51,810	53,980	56,050
5.15	70.00	87.500	14,160	14,300	14,480	14,590	14,730	15,010	15,290	15,863	16,350	18,280	20,020	21,625	23,116	24,516	25,845	27,109	29,468	31,653	33,700	35,623	39,200	42,420	45,453	48,300	50,980	53,530	55,970	58,300	59,712
5.89	80.00	100.000	15,130	15,300	15,450	15,600	15,750	16,050	16,350	16,920	17,474	19,540	21,405	23,120	24,711	26,211	27,630	28,980	31,502	33,840	36,029	38,082	41,910	45,350	48,598	51,630	54,500	57,230	59,830	62,320	64,730
6.62	90.00	112.500	16,050	16,220	16,405	16,545	16,705	17,020	17,340	17,980	18,535	20,725	22,700	24,520	26,111	27,807	29,305	30,735	33,413	35,891	38,211	40,390	41,450	48,100	51,560	54,760	57,810	60,690	63,460	66,103	68,650
7.36	100.00	125.000	16,920	17,100	17,270	17,440	17,610	17,940	18,280	18,920	19,537	21,845	23,930	25,850	27,629	29,308	30,890	32,402	35,221	37,871	40,280	42,580	46,860	50,700	54,327	57,730	60,940	63,980	66,890	69,680	72,360
8.10	110.00	137.500	17,750	17,920	18,111	18,290	18,470	18,820	19,170	19,860	20,490	22,910	25,100	27,110	28,979	30,635	32,402	33,980	36,940	39,670	42,218	44,670	49,140	53,170	57,070	60,541	63,910	67,110	70,150	73,080	75,892

For any pipe larger than one inch, multiply value given by above table by the value under actual diameter as below.

Diameter, inches......	1	1¼	1½	2	2½	3	3½	4	4½	5	5½	5⅝	6	6½	7	8	10	12	16	18	20
Multiplier	1.0	1.562	2¼	4	6¼	9	12¼	16	20¼	25	30¼	31.64	36	42¼	49	64	100	144	256	324	400

[a] To change the result by this table to that for any other specific gravity than 0.6 (air = 1), multiply by $\sqrt{\frac{0.6}{\text{sp. gr. gas.}}}$

Take weight of a cubic foot of air at 0.078 pound.

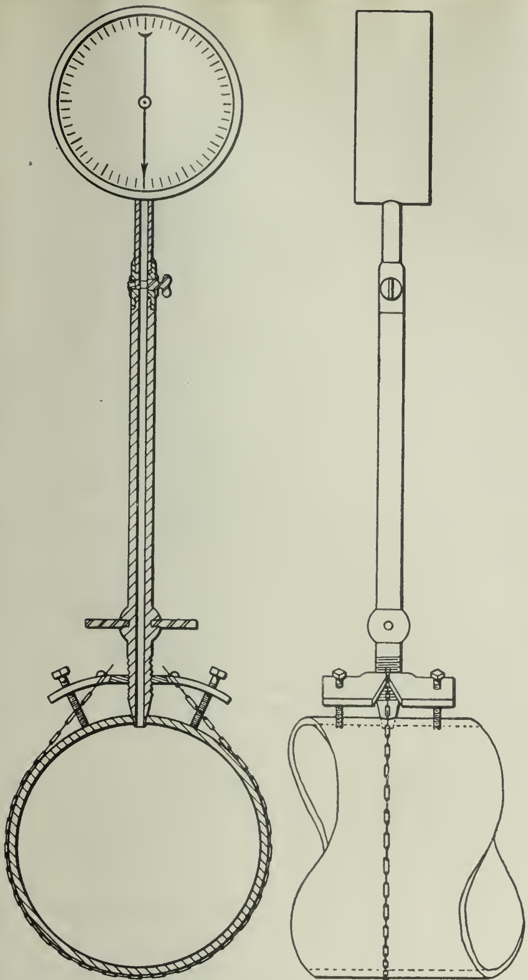


FIG. 11.—Spring gage attached for measuring internal pressure of gas flowing in a pipe.

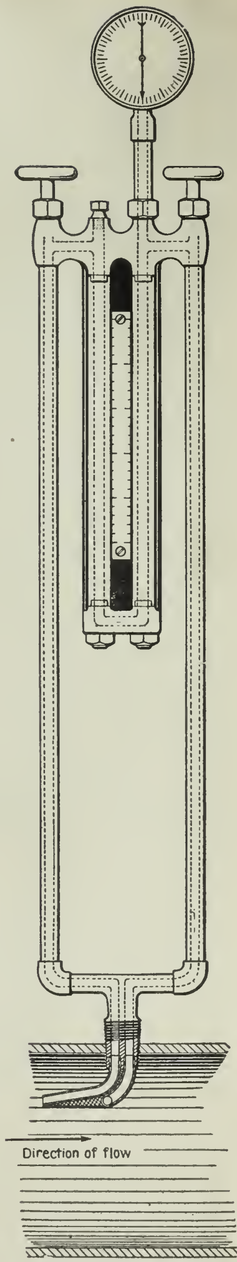


FIG. 12.—Robinson instrument for measuring velocity and pressure of gas flowing in pipes.

spring gage and filling the U-shaped tube in the center of the instrument, may be used as a mercury or water gage. Separate readings of static and flow pressure may be made by closing the valves at the top of the instrument. Tables for avoiding the necessity of computation have been prepared by Professor Robinson for various sized pipes. Corrections may be made in these for difference in specific gravity and temperature.

Minute pressure, or measurement of volume by number of condensations.—If gas is allowed to flow into a reservoir of known capacity the amount which enters may be computed from the increase in internal pressure which accompanies increased density. The casing of a well affords opportunity for similar measurements. If a well is allowed to blow off and is then suddenly closed and the reading of the pressure gage is taken, the density of the gas in the casing at that instant may be determined. If the gage is watched the indicator will show a gradually higher pressure. If this is recorded at the end of a minute the amount of gas which has entered the well casing during that time may be computed by means of the difference in density, the volume of the casing being a readily determinable factor.

In measuring the volume of a well by this method a short piece of tube is attached to the well casing in the same manner as if the static pressure were to be taken, but is so arranged that the well can be blown off. To this tubing a spring or U gage is attached. After the well has been blown off and the index of the gage is stationary the pressure is read and recorded. The control valve is then immediately closed and the time noted. At the end of a minute the pressure on the gage is read and recorded. It will be found to be higher as the result of the compression of the gas in the casing. The difference in pressure is multiplied by the volume of the well tubing in cubic feet and by 0.07 (the constant employed in calculating the number of compressions), and this product is the volume in cubic feet per minute. This quantity multiplied by 60 and 24 gives the volume of production for a day.

This method of measuring the volume of a gas well is the most convenient one yet devised, but although valuable as indicating the relative production which is possible from wells, it should not be considered as accurate.

For computing the volume of a well casing the following table will be found convenient:

Table of diameters in inches, and of contents in cubic feet, for 1 foot of length of well casing.

Diameter in inches.	Cubic feet for 1-foot length.	Diameter in inches.	Cubic feet for 1-foot length.
1	0.0055	6	0.1963
2	0.0219	8	0.3491
3	0.0491	10	0.5454
4	0.0873	12	0.7854
5	0.1364		

OBSERVATIONS AND MEASUREMENTS OF GAS WELLS.

By W. R. Crane.

Measurements of static, or closed, pressure.—The usual method of taking the closed or static pressure of a well when it is free from connecting tubes is to reduce the 2- or 3-inch valve opening by bushings and plugs to a size that will permit the attachment of a pressure gage (see fig. 4). Connection is usually made by a short section of quarter-inch pipe, either straight or formed into a loop such as is commonly known as a steam siphon. If there is a T in the casing below the control valve a lateral pipe valve and elbow will afford a convenient attachment for the gage. Sometimes a hole is drilled into the well tubing a few inches below the control valve, and is threaded, and a short piece of pipe with a valve and a gage connection screwed in. The last two forms of connection are especially convenient where measurements are taken frequently, since they may be left ready for the attachment of the gage. When a gage is attached to a well the joints should be tight. The valve leading to the gage should be opened slowly to prevent too sudden pressure being thrown on the gage. The pressure of the gas will cause the indicator to move until it records a maximum at which it will remain stationary. If the well has not been blown off this pressure will be reached as soon as the valves are fully opened. In case it has been blown off some time will be required for the gas to build up to maximum pressure. Before attempting to remove the gage the valves should be carefully closed. Since there is a wide range of pressures in gas wells, the observer is usually provided with several gages from which he selects one capable of recording the pressure found.

The record of the static pressure in a well is sometimes incorrectly interpreted as indicating the volume of a well. The relation between pressure and volume of flow is variable, and accordingly measurements of flow should be made when the capacity is to be estimated. The observations of static pressure which were taken in the Iola quadrangle were largely for the purpose of determining the hydrostatic conditions in the field and have been of great value in determining the structural relations of the gas-bearing strata.

In studying the hydrostatic conditions of a field it is desirable to learn the initial pressures of wells since they furnish data for estimating the head of water which is pressing upon the gas in a reservoir. When a well is drilled into a sand which has already been tapped by other wells the pressure which it shows is apt to be below that of the first well, since the using of the gas changes the relations in the reservoir. The initial pressures for different parts of the field were obtained from parties who had made observations at the beginning of developments. Some of the pressures have been recorded in published reports or are on record in notes of men who work in the field. The writer measured the pressure in wells in new parts of the field; some of his figures may be regarded as those of initial pressures, since the gas pools had not been drawn upon.

The pressure in the Iola quadrangle varies with the depth of the wells; in round numbers it is 330, 290, 270, and 230 pounds for wells varying in depth between 900–950, 800–900, 700–800, and 600–700 feet, respectively. These figures agree remarkably well with the range of pressures taken throughout the entire field.

As a means of checking the pressure due to hydrostatic head in gas wells, some measurements were made from wells which produce oil. In these cases the pressure recorded was due to the compression of air and gas on top of the oil column when the well was closed. To the pressure shown by the gage was added the weight of a column of oil 1 square inch in section and equal in height to the depth of the oil in the well. An average of a number of measurements made on a group of oil wells showed a pressure of 7.3 pounds on the gage. In estimating the weight of the oil in the well the weight of a column 1 square inch in section and 1 foot high was taken at 0.348 pounds. The total column of oil in the wells in question was 799 feet, equal to 278.4 pounds. The observed pressure of 7.37 pounds added to this gives a total of 285.77 pounds as the hydrostatic pressure in the well. The hydrostatic pressure in gas wells close by which have the same depth was found to be 286.7 pounds. This shows a close correspondence, the difference being about 1 pound. Similar results have been obtained by other observers.

In parts of the field which have been drawn upon very largely the static pressure of wells is generally known to have fallen off. Data obtained during the progress of field work, compared with records made by the writer the previous summer and with the records of other observers, show the decrease to be gradual. Where the wells have been in use for a long time the pressure has been diminished until the consequent production is small, and in some cases the wells have been abandoned. Any notable decrease of static pressure is occasion for alarm as to the continuance of production from a given reservoir. The accompanying table, extending over a considerable period of time, has been prepared from observations on certain wells in the Iola quadrangle.

Table showing decrease of static pressure in certain wells in a part of the Iola field where the consumption is very great.

No. of well.	1900.		1901.			1902.			1903.		
	Sept.	Dec.	Apr.	Aug.	Dec.	Apr.	Aug.	Dec.	Apr.	Aug.	Dec.
	Pounds.	*Pounds.*	*Pounds.*	*Pounds.*	*Pounds.*	*Pounds.*	*Pounds.*	*Pounds.*	*Pounds.*	*Pounds.*	*Pounds.*
1	280	235	190	200	150	85	95	130	100	55	......
2	249	222	185	170	165	130	150	75	65	60	......
3	233	180	187	177	130	145	127	100	85	70	......
4	......	154	150	135	110	122	110	40	2.5	1.5	......
5	......	151	Off.	120	110	86	45	40	Off.	......	......

The initial static pressures, as well as those judged to be somewhat below the initial, obtained from the gas wells in the Iola quadrangle, were platted upon a map, whence it appeared that the low pressures are in the eastern portion of the field and the high pressures in the western. Moreover, zones of equal or of given variation in pressure can be outlined. In the map (fig. 13) zones in which the pressure varies from 140 to 200 pounds, from 200 to 300, and 300 to 330 pounds, are shown. From a consideration of the structure of the field and these zones of pressure the following deductions may be drawn:

1. The trend of the zone is approximately parallel with the strike of the rocks.

2. The pressure increases westward with the dip of the rocks and the static pressure in the wells varies directly with the distance from the outcrop of the gas-bearing formation.

3. The variation of pressure is greatest in pools farthest from the outcrop.

Measurement of the volume of gas wells.—An approximate estimate of the capacity of a gas well can be formed from the sound which the gas makes when it flows into the air. An experienced observer can come within 10,000 to 15,000 cubic feet of the total capacity, but is liable to make a wider error, especially if there are irregularities in the tubing or in the valve which affect the sound. Inasmuch as wells are sold on their purported capacities great care should be exercised in order to guard against misrepresentations. The most accurate method of measuring a well is by means of the Pitot tube (fig. 9). The essential part of this instrument is a U-shaped tube either in a continuous piece or formed by joining straight pieces of pipe by means of elbows. When a tube is made of straight pieces it can be taken apart and cleaned. This is a decided advantage, especially where wells are throwing shale or mud which may clog up the tube. The instrument is attached to a block or saddle which in turn is fastened by means of chains at the top of the well casing. It should be placed at a distance from the control valve. The tube must be free to rotate in the saddle and should be so arranged that it can be adjusted to various sized pipes and brought to any required position over the mouth of the well. When a measurement is made the tube is clamped in the desired position by means of a set screw.

Various devices are employed for attaching the instrument. When a wooden block is used as a saddle it is hollowed at one end to fit the

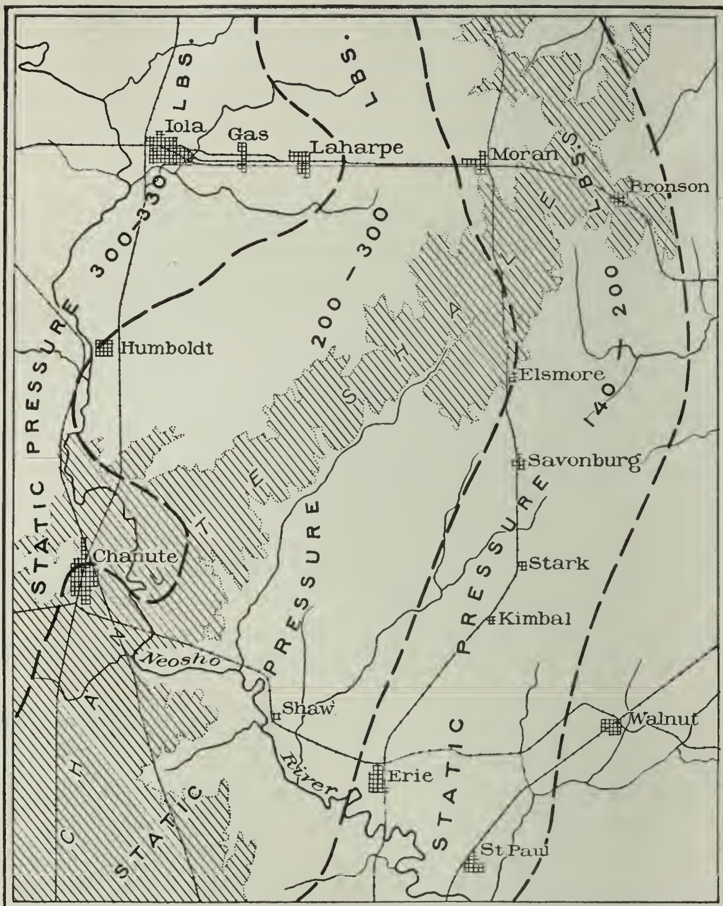


FIG. 13.—Map of Iola quadrangle, showing approximate zones of variation of static pressure of gas wells. The area of outcrop of the Chanute shale is indicated in order to show that the zones are approximately parallel with the strike of the geologic formations.

pipe and slotted longitudinally to allow the adjustment of the tube to the right position in the column of escaping gas. At the end of the block opposite the casing is attached a tightening arrangement operated by a screw. The chains which reach around the well casing are hooked into slots in the ends of a plate. After they have been drawn as tightly as possible about the casing, a few turns of the set screw separate this plate from the block and make the instrument rigid on the well casing. At the end of the U-shaped tube, which is on the outside of the well casing, a pressure gage is attached by means of a flexible hose connection. For strong wells a spring gage is ordinarily used, and for wells having small capacity a gage containing mercury or other liquid is preferable. In adjusting a Pitot tube the mouth should be placed at about the middle of the radius of the casing, at which point the gas flows with a mean velocity. A slight variation in position at this point makes little or no difference, and with a small Pitot tube there is little chance of error.

When a measurement is to be taken the instrument should be attached to the mouth of the well and the tube swung to one side. The well is then allowed to blow off for a period, which varies somewhat with the capacity of the well, but seldom exceeds 4 to 6 minutes. When the accumulated head of gas has been spent the sound made by the gas issuing is uniform and the measurement may be taken. Often the well in blowing off must clear itself of water, mud, and pieces of shale. In such cases the observer must frequently wait 15 to 30 minutes. In rare instances there is no perceptible diminution of ejected material, and measurements are made with difficulty and are liable to be inaccurate, since the mud and shale and water interfere with the flow of the gas and are apt to clog the Pitot tube. When the flow of gas becomes uniform the Pitot tube is rotated over the mouth of the well and clamped in position at the level of the casing. If there is any doubt as to whether the well has blown off a sufficient length of time, the observer should note the register on the gage to see whether it varies, and in case it is found to do so he should wait until it is steady before taking the reading.

The capacity of a well for 24 hours is computed by means of tables which are in common use (see facing p. 50). In stating this capacity the size of the well casing or tubing should always be given, since the capacity varies with the size of the orifice.

The observations taken on wells in the Iola quadrangle show that the flow of gas at different places varies from a few thousand feet up to 10,000,000 feet per day, an average good well flowing about 4,500,000 feet per day. In general the stronger the static pressure of the well the greater the volume of production. Accordingly the best wells are situated in the western part of the area.

The maximum production of a gas well is reached as soon as it has been properly cased and has had an opportunity to clear itself of loose material. From then on it will show a gradual decrease in flow. A good gas well is free from water; the invasion of salt water lessens the value of the well and may entirely stop the issuance of the gas or render it so small as to be worthless. When many wells are drawing upon a reservoir of gas the volume falls off more rapidly, and as the flow decreases it is found necessary to connect more wells with the pipe line in order to obtain the desired amount.

The question which is of vital importance to the industries depending upon gas for fuel is that of the probable life of the field. Since there are undoubtedly a number of gas reservoirs, the question resolves itself into the probable life of the individual reservoirs. Inasmuch as it is impossible to know the vertical and lateral extent of the gas sands, no computation for an individual field can be made on this basis. However, a case may be assumed which will give an idea of the probable life of a gas field. Supposing that a gas sand having a thickness of 40 feet has an areal extent of a square mile, and that the static pressure of the gas is 300 pounds, we may measure the total amount of contained gas. Assuming that the gas occupies a pore or interstitial space in the sand equal to 38 per cent of the total volume (which is a very liberal estimate), 2.6 cubic feet of the sand would contain 1 cubic foot of gas at a pressure of 300 pounds, or 12.36 cubic feet of sand would contain 100 cubic feet of gas at atmospheric pressure. An area of sand 1 foot in thickness and having an extent equal to 1 acre would contain 43,560 square feet of gas at atmospheric pressure. If the sand is 40 feet thick and has the same extent, it contains 14,097,080 cubic feet, and in a square mile of 640 acres there would be 9,022,131,200 cubic feet of gas. To render this calculation more convenient for reference in computing for sands of various thickness and extent, the following table is presented:

Contents of gas under a pressure of 300 pounds per square inch in sands having 38 per cent pore space.

Thickness of sands in feet.	Cubic feet per acre.	Cubic feet per square mile.
1	352, 427	225, 553, 280
10	3, 524, 270	2, 255, 532, 800
20	7, 048, 540	4, 511, 065, 600
30	10, 572, 810	6, 766, 598, 400
40	14, 097, 080	9, 022, 131, 200

Assuming that the average daily output of a well is 4,500,000 cubic feet in 24 hours, the theoretical life of a well drawing upon a 40-foot sand bed under the conditions above outlined would be 2,004 days, or 5.5 years. However, variations in conditions of pressure during the life of the well change the time limit at which the sand will be exhausted. The life of the well, however, would not be much over 5 years. This calculation is based upon the open flow of the well—that is, the flow of gas into the air. A well, however, would not maintain a steady, uniform flow for a number of years, and when connected with a pipe line will exhaust itself much less quickly, since the total volume is seldom utilized.

Considering the problem of the life of a well from the standpoint of decrease in pressure, it is found that the above figures are largely corroborated. A decrease in static pressure of 4 pounds per month (a range of from 3 to 5.5 pounds has been observed) is about the average for the field. Some observers claim a decrease of 5 pounds per month. Few wells are considered to be of much importance after the pressure has fallen below 50 pounds. If the initial pressure is 300 pounds and the rate of decrease is 4 pounds per month, the life of the well, provided other conditions remain the same, would be 5.2 years, which corresponds closely with the time limit of 5.5 years given above. It should be remembered that the invasion of water or oil is liable to change the conditions of production at any time. If a decrease of 5 pounds per month is noted, the life of the well would be 4.1 years. The results in either case agree approximately with the experience of gas consumers in this field.

Measurements of flow of gas in pipes.—As already described on page 49, the Pitot tube may be used in measuring the volume of gas flowing through a pipe. If the Robinson instrument is used, a hole is drilled into the pipe and threaded, and the Pitot tube is screwed in, making a tight connection. The lower end of the tube, which must be turned parallel with the axis of the pipe, should be so inserted that it may be in the neutral zone or at the point of average velocity. With the Robinson instrument the pressure due to the velocity of flow may be measured, and from this the volume of gas passing through the pipe may be computed.

The forms of instrument shown in figs. 10 and 11 may be attached to the service pipe by drilling a hole and reaming it, the connection being made tight by the pressure of the steel point when the set screws on the saddle are turned. With these instruments the static pressure and the combined static and flowage pressure are measured and the pressure due to the velocity is found by subtracting. After the measurements are made the hole in the service pipe can be closed by driving in a portion of a large wire nail which has been tapered.

It is frequently desirable to know the amount of gas which is supplied throughout the day by a service pipe. In such a case the instruments may be connected with a recording pressure gage, such as a Bristol gage, which furnishes a chart of the pressures throughout 24 hours. Two charts are usually secured—one showing the static pressure and the other the static plus the flowage pressure. By deducting the former from the latter the flowage pressure is obtained. This method of taking flowage pressure has several advantages over the use of water or mercury gages or occasional readings with spring gages, since it is mechanical, and therefore positive, and the charts can be studied at leisure. Pl. X shows the records taken from a service pipe during 24 hours; the irregularities in the record line correspond with the increased or decreased amount of gas used by the plant; the jogs at 5 a. m. and 6 p. m. correspond with the closing and opening of certain of the burners for the changing from night work to day work, and vice versa.

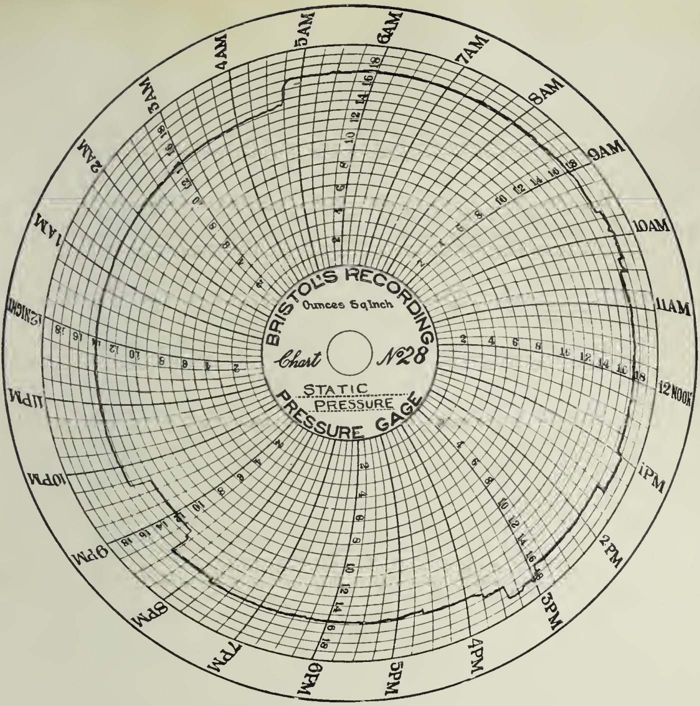
OBSERVATIONS ON METHODS OF DEVELOPING AND UTILIZING OIL AND GAS.

By W. R. Crane.

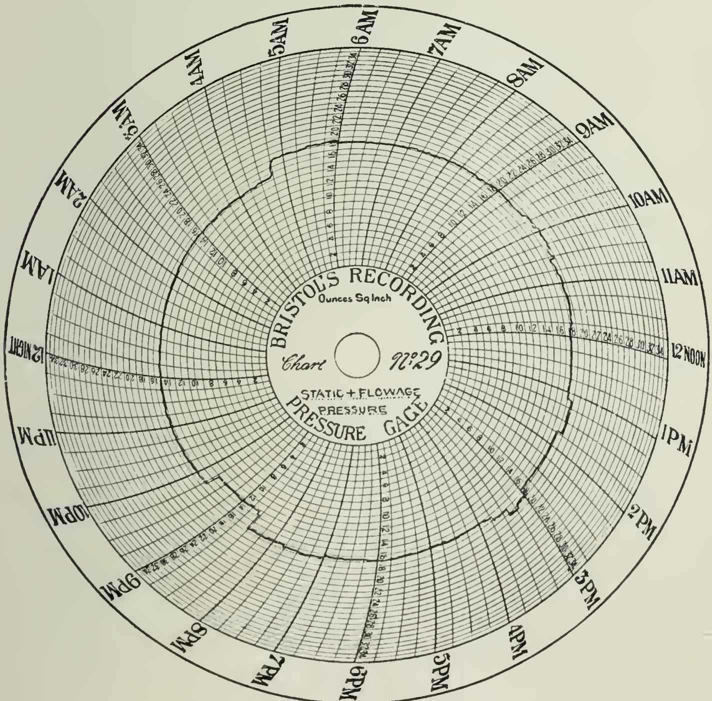
Methods of drilling.—Prospecting and drilling for both oil and gas is done by the American cable tool, or oil-well, system, for which there are three different forms of drilling devices—the standard or carpenter's rig, the rig and reel, and several styles of self-contained rigs. The order in which the drilling rigs are mentioned is in accordance with their adaptability to heavy work and deep drilling. The wells in the Iola quadrangle range from 500 to 1,500 feet in depth. The formations, as a rule, are easy to drill through, being composed principally of shales, sandstones, and some limestones. The shales predominate through probably seven-eighths of the thickness of the rocks encountered. In drilling through limestone the operation is commonly called "spudding" (a term applied to drilling through hard rock), this being the most difficult part of drilling. When a well starts in limestone no conductor is employed; in other portions of the field about 20 feet of conductor is required, for which purpose an iron casing, or a tube made up of eight wooden staves, is used. The shales, especially when charged with water, are moderately soft, and the holes must be promptly cased in order to prevent caving. The casing is usually carried to within 20 or 30 feet above the cutting bit and driven as the hole is deepened. It can be readily forced through the soft shales, but where hard sandstones and limestones are encountered it is necessary to ream the hole.

The usual height of derricks in the field is from 50 to 65 feet, varying with the length of the string of tools. Even with such comparatively low derricks considerable damage is done by windstorms, which occasionally wreck them. Accordingly many operators stay the derricks with guy ropes. After the wells are completed the upper portion of the derrick is lowered to a height sufficient for handling the casing in subsequent work on the wells.

Cost and rate of drilling.—Oil and gas wells are usually drilled by contract at a charge of 80 cents to $1 a linear foot, not including the cost of fuel and water. The speed of drilling ranges from 50 to 125 feet a day, a fair average being about 100 feet, a rate, however, which can not be attained in the harder rocks. The fuel used is either coal or natural gas. Coal is more expensive and more inconvenient to



A. CHART OF STATIC PRESSURE IN SERVICE PIPE TAKEN WITH BRISTOL'S RECORDING PRESSURE GAGE.



B. CHART OF STATIC FLOWAGE PRESSURE IN SERVICE PIPE TAKEN WITH BRISTOL'S RECORDING PRESSURE GAGE.

handle, costing about $40 for a hole 1,200 feet in depth. Where natural gas is employed it is customary to pay $50 per hole for the privilege of drawing a supply from the neighboring well; occasionally, however, the gas is sold at a fixed price for each foot drilled, a common charge being 5 cents per foot. The cost of a drilling rig varies according to the style used, but is somewhere about $2,500 or $3,000, including all tools. The labor item is by far the most expensive, ranging from 18 to 22 cents per foot. If the drilling results in a producing well the contractor finishes the well; that is, cases, tubes, and packs it, charging the owner with the actual cost of the materials used.

Systems of oil pumping.—There are several systems used in pumping oil from still or quiet wells, designated "shacklerods" and "compressed air." In the latter method air is forced into the tubing and the oil driven out through a smaller pipe. In other cases 2-inch and 1-inch pipes are inserted side by side, the smaller pipe making connection with the larger at a point a few inches above the end of the same; at the lower end of the larger pipe is attached a ball valve through which the oil enters, when the air entering the larger pipe from the smaller produces a suction; this constitutes what is commonly known as the geyser valve.

Shacklerods are used when wells are pumped. The power is communicated by a device capable of producing a reciprocating movement, commonly an eccentric, and is transmitted by rods, ropes, or wires. A single power plant may operate a large number of wells. The rods, ropes, and wires which run to the pumps are guided by supports which are placed short distances apart, and are known as "holders up," or if depressions are crossed are called "holders down." Rods are preferred on level ground, while ropes and wires are adapted to rough, uneven surfaces.

Distribution and control of gas supply.—Gas as it comes from a well is under too high pressure to be utilized, and must have its pressure reduced. This is accomplished by so-called reducing valves, which act automatically and are controlled by the pressure of the gas. For ordinary purposes the pressure must be reduced to 4 or 8 ounces from an initial pressure of 300 pounds, more or less, necessitating reduction by stages in order to do it safely. Two regulators are usually employed, the first reducing to 60 pounds and the second from 60 pounds down to the desired number of ounces. The gas enters the automatic reducer exerting its pressure on a relatively small surface and passes out through a larger chamber. The total pressure on the opposite sides of a diaphragm being exactly balanced, is less per square inch on the larger area.

Aside from the regulation of the pressures the supply is also controlled by receivers, usually placed near the point of consumption. These, as commonly constructed, are made of several 100- to 150-foot lengths of 6- or 8-inch pipe placed parallel and several feet apart, the ends being suitably connected with elbows and nipples. They constitute a portion of the main line and are provided with valves at both ends to control the flow of gas. The function of the receiver is to give a slight reserved capacity to the system by adding to the storage capacity of the main line near the point where it is drawn upon. It also serves to reduce pulsations in the flow of the gas.

It is considered one of the most difficult tasks in operating a gas line to keep it open during all seasons of the year, especially during cold weather. Formerly a crew of men were detailed to thaw out the pipes and regulators during freezing weather, but even with this precaution the pipes would frequently freeze and burst or become stopped up in whole or in part. If the wells are wet, or if even one wet well is connected with the system, serious trouble is experienced, and even with the driest wells some moisture accumulates in the pipes. The best methods for controlling supply employ drips and heaters, the former to remove the accumulated water and the latter to keep the gas at a temperature above freezing and prevent the condensation of water and the formation of ice and frost in the pipes. Drains are usually constructed of pipes ranging in length from 6 to 12 feet, with a diameter of from 6 to 8 inches. These are placed several feet below the intake pipe and are usually buried 2 or 3 feet below the surface of the ground. They are provided with caps at the ends, connection being made with the intake and discharge pipe by saddles or tees at both ends, the two pipes entering on the upper side. The gas enters with its burden of water at one end and loses it, or a large part of it, in passing to the point of discharge. Drains are usually placed at or near the points of consumption, although they are often placed along the pipe lines, in which case they are commonly called "bleeders." Heating devices are placed at intervals along the gas-pipe line and are usually situated on the low-pressure side of regulators at a distance of from 50 to 75 feet away. They are constructed by excavating a trench about 3 feet deep, 2 feet wide, and 25 feet long, walling it up and arching it over with brick. A hole is drilled into the pipe line on the lower side close to the open end of the furnace and a half-inch pipe provided with a valve screwed in and turned by means of an elbow, so as to run parallel with the main line and at a distance of from 4 to 6 inches below it. This pipe is perforated on the upper side and plugged at the rear end and is converted into a burner which can be used under the gas flowing in the main line.

Heaters are placed on the low-pressure side of regulators for the reason that gas loses much of its heat on expanding, and it is accordingly on this side of the regulators that freezing is more apt to occur. Heaters, of course, are not employed during warm weather, but drains are in constant use.

Formerly when the static pressure was high it was the common practice to use small pipes for conveying gas considerable distances, but, nowadays, as the pressure falls off, or the gas is taken from weak wells, it is necessary to use larger pipes. Accordingly, for a line of say 8 miles, instead of the 4- and 6-inch pipes once in common use, pipes ranging in size from 10, 8, 6, and 4 inches are now employed in different sections in the order mentioned. It is claimed by gas companies that an 8-inch pipe line presents a resistance which reduces the pressure 9 pounds a mile. While this estimate may be rather high it gives an idea of the difficulties encountered in maintaining service through supply pipes.

PORTLAND CEMENT.

The large supply of natural gas in Kansas which is available as fuel, together with the inexhaustible deposits of materials suitable for the manufacture of cement which are located in the gas field, has brought about the introduction of the Portland-cement industry in the State. The Iola Portland-Cement Company's plant at Iola (Pl. XI, *B*), completed in 1900, enjoys the distinction of being the first one to use natural gas for fuel. It has a capacity of 3,000 barrels per day. A second plant, which will have a capacity of 1,500 barrels per day, has been located near Iola and is now nearing completion. Three or four additional cement plants are projected for near-by portions of the State and probably some of them will be built. Because of the importance of this industry and because it promises to assume greater proportions in the Kansas field, it is thought best to give a rather full discussion of the processes of manufacture.

TYPES OF SILICATE CEMENTS.[a]

There are three types of cement manufactured in the United States which may be classed as silicate cements. They agree in being hydraulic, though in different degrees, and in the fact that this property is due principally to the formation of tricalcium silicate.

Puzzolan cement.—The least important class of silicate cements is puzzolan cement, produced by the mechanical mixture, without calcination, of slaked lime and silico-aluminous material, the latter being either a volcanic rock or blast-furnace slag. Of this class about 500,000 barrels were manufactured in the United States in 1903.

Natural cement.—Next in importance are the natural cements, which are produced by the calcination, at a temperature below that of clinkering, of a clayey limestone (which may or may not contain a notable percentage of magnesia) in which the quantity of lime (plus magnesia) is so low relative to the silica and alumina that little or no free lime appears in the cement. Of this kind of cement about 7,000,000 barrels

[a] See Eckel, Edwin C., Municipal Engineering, vol. 24, May, 1903, p. 335; also vol. 25, July, p. 1.

were manufactured in the United States in 1903. The plant at Fort Scott, Kans., manufactures this class of cement.

Portland cement.—The most important type is Portland cement, which is produced by the calcination, at the temperature of semivitrifaction (clinkering), of a mixture of calcareous and clayey materials in the proportion of about three parts of lime carbonate to one part of silica and alumina combined. About 16,000,000 barrels of Portland cement were manufactured in the United States in 1903. The cement manufactured at Iola is of this type.

CHEMICAL COMPOSITION OF PORTLAND CEMENT.

A comparison of the results obtained by analyzing many of the best grades of cement, both domestic and foreign, warrants the limitations in composition between certain percentages, which are set forth in the annexed table, which contains data already frequently published:

Chemical composition of different Portland cements.

	Minimum.	Maximum.		Minimum.	Maximum.
	Per cent.	*Per cent.*		*Per cent.*	*Per cent.*
Silica, SiO_2	19	26.0	Magnesia, MgO	0	5.0
Alumina, Al_2O_3	4	10.0	Sulphuric acid, SO_3	0	2.5
Iron, Fe_2O_3	2	5.0	Alkalies, K_2O and Na_2O	0	2.8
Lime, CaO	58	67.0			

As has already been stated, silicate cements owe their properties principally to the formation of a tricalcium-silicate molecule, 3CaO, SiO_2. This was first suggested by Le Chatelier.[a] The tricalcium-silicate molecule is accompanied by varying amounts of similar molecules containing calcium and aluminum, and calcium and iron, the exact formulæ of which are not as yet so well understood. Le Chatelier[b] gives them as 3CaO, Al_2O_3, and 3CaO.Fe_2O_3, while Newberry[c] holds they should be 2CaO, Al_2O_3, and 2CaO.Fe_2O_3.

According to Newberry's formula, the ratio between lime and silica is about 2.8 to 1; between lime and alumina, about 1.1 to 1, and between lime and iron oxide, about 0.7 to 1. It is evident, therefore, that the per cent of lime required will vary with the amount of alumina and iron present. Should a cement be composed entirely of the lime-silica molecule it should have about 73.7 per cent of lime and 26.3 per cent of silica to correspond with the above formula; should it be composed entirely of the lime-alumina molecule it would have but a little over 52 per cent of lime; and if composed entirely of the lime-iron molecule it would contain only 41 per cent of lime. It is

[a] Annales des Mines, 1887, p. 418. [b] Op. cit., p. 418. [c] Jour. Chem. Ind., 1897, p. 889.

evident, therefore, that the higher the proportion of iron and alumina the lower will be the proportion of lime and silica.

At present it is a little uncertain just what effect the alumina and iron have on the cement. Evidently they lower the fusion point of the clinker, and therefore reduce the cost of burning, particularly of the iron, and a proper amount of them is therefore desirable. The pure lime-alumina cement, made in laboratories, sets very quickly, indicating that the alumina tends to reduce the time of setting. A pure lime-iron cement, made by Doctor Schoch, would not set under cold water but did so readily under hot water, making a pat of constant volume and great strength. It is generally believed that the combined alumina and iron oxide should not exceed one-half the amount of silica. A desirable shale, therefore, is one which has some alumina and iron oxide in it to render the clinker more easily fusible, and at the same time not enough to make the cement too quick setting nor to reduce the proportion of the tricalcium-silicate molecule too greatly.

Certain objectionable elements, such as magnesia and sulphur, which may exist as impurities in the limestone, shale, or fuel are to be avoided. It is generally believed that magnesia is objectionable when present in quantities greater than 3 to 5 per cent. Years ago engineers generally held that not exceeding 2 per cent of magnesia should be present; later they raised this to 3 or 4 per cent, and now many of them admit that 5 per cent is allowable. Similarly, the amount of sulphur should not be very great—just how great is variously stated by different engineers.

It is probable that the particular condition in which the sulphur exists is an important consideration. In the form of calcium sulphate it is less objectionable than when in the form of calcium sulphide, as in the latter case the sulphur readily unites with the iron present and later is oxidized to iron sulphate, which first swells up and cracks the cement and later dissolves out, each process tending to destroy the cement. In the table quoted above the sulphur trioxide is limited to 2.5 per cent, yet when plaster or gypsum is added to retard the setting this amount may be considerably exceeded, since the sulphuric acid thus added, being already in combination with lime, can not exert any considerable chemical influence on the cement itself. During the last two years the price of good coal has been so high that many cement manufacturers have, it is reported, resorted to the use of cheaper coal, using some carrying so much sulphur that they would have rejected it previously. In this way, it is said, cement with the sulphur content considerably beyond the danger line as previously fixed has been forced on the market, without any bad results following.

By way of summary, then, it may be stated that a good Portland cement can be made from a limestone carrying from 75 to 100 per cent of calcium carbonate, by mixing it in proper proportions with clay or clay shales, provided the impurities present in the limestone are principally silica, alumina, and iron, and provided, further, that neither the limestone nor the shale has sufficient magnesia or sulphur to exceed the limits above stated. A limestone having from 85 to 90 per cent of calcium carbonate may be, therefore, just as desirable as one theoretically pure. The clay and clay shales may have a high proportion of lime present, as many of the Kansas shales do, and still be very desirable, for the lime in the shale will serve the same purpose as lime in the limestone. The main features to guard against are too large an amount of magnesia or sulphur, and an amount of alumina and iron oxide combined not equal to one-half the amount of the silica.

Physical properties.—Careful chemical tests are made at each step during the process of the manufacture of cement. Similarly, the finished product is subjected to careful tests, records of which are retained, showing the character of the cement going out in each shipment. All the physical properties which are desirable in cement are summarized below:

Gravity, 3.15 to 3.25.

Time of setting: Quick setting; initial set, 15 to 25 minutes; final set, not over 2 hours. Ordinary setting; initial set, 45 to 60 minutes; final set, not over 8 or 10 hours

Fineness: 100-mesh sieve, not more than 10 per cent residue; 200-mesh sieve, not more than 25 per cent residue.

Tensile strength: Neat: 24 hours, 250 pounds per square inch; 7 days, 450 to 500 pounds; 28 days, 550 to 800 pounds. Three parts sand mortar and one part cement: 7 days, 175 to 200 pounds; 28 days, 225 to 400 pounds.

Soundness: Should not check nor crack when tested in cold or hot water or steam, but should maintain a constant volume throughout.

RAW MATERIALS USED IN THE MANUFACTURE OF PORTLAND CEMENT.

Siliceous and pure limestones.—About 67 per cent of the Portland cement manufactured in the United States in 1903 was made from a mixture of argillaceous limestone and pure limestone, the principal material being argillaceous limestone which approximates the ideal Portland-cement material, the pure limestone used being added to obtain the proper composition.

Marl and clay.—Calcareous marls obtained from lake basins are extensively used. Inasmuch as they are usually quite pure lime carbonates, they require the addition of clay to bring them up to the proper composition for Portland cement. About 12 per cent of the cement produced in 1903 was of this kind.

Chalky limestone and clay.—Chalky limestones vary from rather pure calcium carbonate, low in both magnesium and clayey materials, to an impure clayey limestone requiring little additional clay to make it fit for use in the manufacture of Portland cement. About 5 per cent of the cement produced in the United States in 1903 was manufactured from such material.

Caustic-soda waste and clay.—Precipitated lime carbonate, which is a by-product in the manufacture of alkali, may be combined with clay material for Portland cement. However, there is not much of it used.

Slag and limestone.—Slag running high in lime, which is a by-product of blast furnaces, may be mixed with pure limestone and burned to form Portland cement, but cement of this class amounts to but a very small per cent of the annual production.

Pure (hard) limestone and clay or shale.—These materials are the ones used in the manufacture of cement at Iola. The limestone, being relatively pure, requires the addition of a considerable amount of clayey material in order to produce the desired combination. About 13 per cent of the Portland cement manufactured in the United States is from such material.

CEMENT MATERIALS IN THE IOLA QUADRANGLE.

There is practically no limit to the amount of Portland cement that might be manufactured from limestones and shales located within the Iola quadrangle. There are several localities at which materials of suitable chemical composition and physical properties may be obtained, and the location of the cement plants thus far has been chiefly determined by the availability of gas, water, and railway facilities. The limestone used is from the Iola formation, which occurs in a heavy bed and is quite uniform in character, and the shale is from the Concreto formation which overlies the limestone. The relation of these two formations is particularly fortunate, and the fact that the shales occur in hills rising above the limestone has made possible the location of the plants conveniently near both materials.

The geologic map accompanying this report (Pl. I) shows the limits and extent of the limestone and the shale formations. Not all of them are suitable for the manufacture of cement, and in some cases it is impossible to find both shale and limestone at the same locality. The Iola quadrangle, however, may be considered as capable of supplying all the material which the industry may demand, and bids fair to become the center of the cement industry in the State.

CEMENT PLANTS AND PROCESSES OF MANUFACTURE.

The plant of the Iola Portland Cement Company, situated just south of the limits of Iola, was the only one in operation in 1903. The Kansas Portland Cement Company, located about a mile northeast of Gas, a station 2 miles east of Iola, will begin manufacturing early in 1904. The two plants are similarly situated. They are located at the base of hills from which the shale is obtained, the limestone being quarried at a slightly lower level near by.

Iola Portland-cement plant.—The first process in the manufacture of cement is the quarrying of the material. At the Iola plant the shale is dug from the side of a mound and the pit accordingly requires no artificial drainage, while the limestone which is used lies below the level of the ground and must have its pit pump (Pl. XI, *A*). The limestone is quarried by means of heavy blasting, which breaks it into large pieces, some of which require additional breaking in order to reduce them to a size that permits easy handling. Both shale and limestone are transported to the mills by means of a steam tram.

The next process is the crushing of the material. The limestone is put through a Gates crusher and the shale through a Williams mill. The material is then dried so that it will not clog in the subsequent process of pulverizing. It is then finely ground in Griffin mills, after which water is added to it, and it is agitated in pug mills.

Water is used in mixing the materials, the method being known as the wet slurry process. The shale and limestone are stirred together in a large tank from which the mixture is conveyed by means of pipes. It is essential at this stage that the slurry should be of the proper composition. An attempt has already been made to govern this in a rough way by using definite amounts, by weight, of the shale and the limestone, and when the material has reached the slurry tanks chemical analyses are made and the additional amounts of limestone or shale, which the mixture may require, are added before it goes to the furnaces. At this plant 21 rotary furnaces are installed, yielding 3,500 barrels per day of 24 hours. They are made of heavy boiler steel in the form of a tapering cylinder, about 60 feet in length and 8 feet in diameter at the larger end. They are lined with fire brick, which reduces the internal diameter to about 6 feet at the front end and to between 4 and 5 feet at the rear or smokestack end. They are mounted on trunnion and cog gearings which give them about 2 revolutions per minute. The slurry is automatically fed into the smaller or upper end of the kiln and the gas into the opposite end; the blaze travels through the kiln, producing the greatest heat near the burner. The inclination of the kiln causes the slurry, which is prevented from coking by the rotation of the kiln, to travel toward the lower end, thus becoming heated gradually. As it passes the hottest place in the furnace it is fused into what is known as clinkers, in the form of little balls from one-half to one inch in diameter, which roll out at the lower end of the kiln into a conveyor. After the clinker has cooled it is pulverized by Griffin mills and conveyed to storerooms, where it is held for shipment. Before grinding, however, a minor amount of crude gypsum is added in order to retard the set. The sulphur trioxide

A. LIMESTONE QUARRY AT THE IOLA PORTLAND CEMENT COMPANY'S PLANT.

B. IOLA PORTLAND CEMENT COMPANY'S PLANT.

of the gypsum combines with the lime alumina of the cement, which would otherwise be quick setting.

Kansas Portland-cement plant.—This plant, which will begin operations early in 1904, is similar in a general way to the one just described; the materials used are the same and will be obtained by the same methods. The limestone will be ground by an Austin No. 8 gyratory crusher, which will receive the rock directly from the quarry. It will then be passed through a revolving screen which will take out about two-thirds of the material and send the remainder to a No. 5 crusher. The shale will be treated first with a Williams pulverizer and the raw material finally pulverized by Griffin mills set in wooden frames. The plant will have 8 rotary kilns, giving a capacity of 1,500 barrels per day of 24 hours.

BRICKMAKING.

CHARACTERISTICS AND PROPERTIES OF CLAYS.

Definition and composition of clays.—Clay may be defined from a physical standpoint as a variable mixture of fine-grained mineral fragments possessing, when wet, the property of plasticity which permits it to be molded into any desirable shape, and, when subsequently dry, to retain that form. The mineralogical constituents of a clay are hydrated aluminous silicates, free silica, iron oxide, carbonate of lime, and fragments of various silicate minerals in more or less decomposed condition that have survived the destructive agencies to which they have been subjected. When examined chemically the components, in addition to chemically combined water, are found to be silica, alumina, iron oxide, lime, magnesia, potash, and soda, together with small amounts of titanic acid, sulphuric acid, manganese oxide, phosphoric acid, and organic matter. The hydrated silicate of alumina known as kaolinite is commonly spoken of as the clay base; it is derived from the decomposition of feldspars. The additional substances in clays are due to the varying amounts of other mineral matter which was present in the original rocks or which has subsequently become mixed with the kaolinite.

When a clay is heated above a certain temperature it forms a hardened rock-like mass which if reground no longer shows plasticity. In the process of burning certain substances in the clay assume a glassy form. Commonly, in burning clays, three stages are recognized, namely, incipient fusion, fusion, and viscosity, according to the degree of completeness of the fusion. The substances which fuse readily are spoken of as fluxing materials, and the more refractory are spoken of as nonfluxing. However, if the temperature be sufficiently high all the elements in the clay will fuse.

Classification of clays as to origin.—Clays may be classified as residual and transported clays. Residual clays are formed by the disintegration of rocks in place. The original sources of all clay material are igneous rocks, the decomposition of their mineral elements, especially the feldspars, giving rise to a surface layer of clay. Similarly, stratified rocks upon weathering produce clays, the percentage of clay varying according to the nature of the rocks. Examples of clays originating in this way are the disintegrated surfaces of shale beds and the clays which result from the solution of limestones. Such clays approach very closely to the condition of soils.

Transported clays are those that result from various mechanical agencies which have removed disintegrated rock materials from the place of origin. Silts which have been transported by running water, glacial drift which has been produced by the action of ice, loess which consists largely of wind-blown material, and shales which are derived from clay deposited in lakes and oceans, are all transported clays.

It is possible that certain clays have resulted from precipitation and are accordingly of chemical origin.

Classification of clays as to uses.—Aside from the uses to which clays are adapted, either without artificial preparation or by the admixture of additional materials, they are the source of a large number of manufactured products. These may he classed as (1) paving brick; (2) common brick, front brick, washed brick, terra cotta, roofing tiles, decorative tiles, terra-cotta lumber, and enameled brick, used in building and decorative art; (3) hollow ware, including drain tiles and tile pipes, used for engineering and hygienic purposes; (4) refractory products, including fire brick, glass pots, and gas retorts, used in manufacturing and engineering industries; (5) pottery and porcelain, including washing clays and slip clays, used for domestic and decorative purposes.

CLAYS IN THE IOLA QUADRANGLE.

The formations of the Iola quadrangle are all stratified. The residual clays derived from them are rather unimportant. Formerly they were used to a limited extent in the manufacture of common brick, the material utilized being more or less mixed with organic matter and therefore largely in the nature of a soil. Deposits of this nature are usually thin and variable.

There are a number of important shale beds within the area which, upon being ground, furnish a clay suitable for the manufacture of paving brick, common brick, hollow ware, and common pottery. Thus far the only use made of them is in the manufacture of common brick for buildings and sidewalks. The shales used, although coming from different geologic formations, are similar in all instances. The bricks are burned with natural gas, and the cheapness of this fuel has stimulated the development of this branch of manufacture. Thus far no plant has been erected for the manufacture of vitrified or paving brick, this being due partly to the fact that the demand has been principally for common brick, and partly because the paving brick needed has been supplied from plants outside of the quadrangle. The construction of down-draft kilns would probably permit the burning of vitrified brick; some experiments have already been undertaken along this line. In adjacent portions of the State some hollow ware and pottery are manufactured from the same class of shales that are found within the Iola quadrangle.

CONDITION OF THE BRICK INDUSTRY.

Brickmaking is an important industry in the vicinity of Chanute, Humboldt, Iola, and Laharpe. The great bulk of the product is sold at home, the demand for building brick having been very large on account of the growth of towns where industries using oil and gas have been established. The capacities of the plants have outstripped the local demand and bricks have been shipped as far south as Galveston, as far west as Albuquerque, and north and east far beyond the limits of the State. For three or four years conservative business men have been arguing that the demand for brick was unnatural and that the rapid establishment of plants would soon result in so great a production that the prices would be lowered almost to the point of cost, but such predictions have not yet been verified, the market for the season of 1903 being better than at any other time since brickmaking was begun in the gas belt. What the further development will be is a mere guess, but it seems probable that there will be no material decrease in the near future. During 1903 approximately 65,000,000 brick were manufactured at the plants described below, with a value, at the factories, of about $325,000.

Brick plants at Chanute.—Two brick plants are located at Chanute, one about 2½ miles south of town, within the Iola quadrangle, the other about 3 miles southwest of the town, one-half mile outside the quadrangle. The plant south of the town belongs to the Coffeeville Vitrified Brick and Tile Company. It has 7 kilns, with a capacity of 300,000 brick each and an aggregate capacity of from 60,000 to 75,000 brick each 24 hours. The kilns are of the ordinary kind, open at the top, except when temporarily closed with each charge. Gas is admitted on each side at the base. The kilns are stationed side by side about 20 feet apart. A large supply pipe rests on top of the ground midway of the alley between each two adjacent kilns, with 18 side lines, laid about 3 feet apart, leading to each, giving 36 burners to each kiln. A mixer with a 3-inch cross section is placed on each side pipe just outside the kiln. The temperature of the kiln is controlled largely by the amount of air admitted. Instead of regulating the amount of gas entering the kiln it seems to be more convenient simply to regulate the amount of air, which is easily done by adjusting the collar on the mixer so as to make larger or smaller air openings and in this way control the amount of actual combustion.

Steam power is used throughout the plant, the steam being generated in boilers by burning gas. Two boilers, with an aggregate capacity of 180 horsepower, furnish the necessary steam, which is used in one engine with a capacity of 128 estimated horsepower.

The shale is first pulverized by passing through an ordinary dry-pan pulverizer. From here it goes to the pug mill, where it is tempered by a stream of water properly controlled, and passes on to the auger and out onto the belt conveyer, as customary in modern brick plants. A rotary cutter, with 22 wires, with a maximum capacity of 125 brick per minute, cuts the clay into brick, which are then carted away to a gas-heated drying room, whence they are built directly into the kilns.

The mine, or shale pit, is a few rods north of the mill and is sunk downward from the surface, the shale being drawn up the incline in cars operated by a cable from the mill. As the pit now appears its walls present a vertical section of about 60 feet. A sandstone at the top is 12 feet thick at the north side of the pit, but decreases southward, owing to surface variations, to a thin edge, where mining first began. Shale underlies the sandstone, continuing to the bottom of the pit and probably much deeper. About 5 feet below the bottom of the sandstone is an 18-inch bed of limestone, as seen at the south end of the pit, which gradually decreases northward and entirely disappears 75 or 100 feet before the north end of the pit is reached. Below the limestone the shale is uniform in character, fine-grained, dark gray in color, and practically free from sand.

In operating the mine the material is first loosened or broken down by blasting. An ordinary power churn drill is operated in the sandstone, which is first blasted off and carried away, so that the breast of sandstone precedes the breast of shale by a few feet. All the loose sand and the smaller fragments produced by the shot are mixed in with the shale, and help to prevent shrinkage while firing the brick. The shale is drilled by hand drills of the auger type, two men drilling a hole 5 feet deep in from 30 to 45 minutes.

The plant southwest of Chanute, owned by the Kansas Vitrified Brick Company, and lying outside the limits of the Iola quadrangle, obtains its shale from the Concreto bed, which overlies the Iola limestone. The company manufacture the same kind of brick as those already described, its plant is similar, and its shale obtained from a pit level with the surface of the ground. There is not enough difference in the general properties of the two shales to enable one to distinguish between them by examining hand samples. A description of one plant is, therefore, practically the same as a description of the other.

Brick plant at Humboldt.—One brick plant is located about 1¼ miles north of Humboldt and is owned by the Humboldt Brick Manufacturing Company. It began operations in the spring of 1898 and has a capacity of 40,000 brick a day. Its machinery consists of the regulation dry pan for crushing the shale and a pug mill and auger for molding the brick. This company is making a specialty of sidewalk brick, which they re-press, producing a variety of patterns on the top side of the brick.

The plant is operated throughout by gas for fuel. Steam power, generated by burning gas, is used, and the kilns are fired by gas, being arranged practically the same as those of the Chanute plant. The shale used lies on the surface adjacent to the plant and is obtained by sinking a pit, the material being serviceable almost from the surface of the ground. As these shales lie almost on top of the Iola limestone they belong to the Concreto horizon, the same used by the Kansas Vitrified Brick Company for its plant southwest of Chanute. The quality of the shale here is practically the same as at Chanute, and the quality of the brick likewise, whatever differences may be observed being due principally to slight differences in manufacturing processes.

Brick plants at Iola.—There are 4 brick plants at Iola, 2 owned by the Iola Brick Company, 1 by the Star Brick Company, and 1 by the Home Brick Company.

The Iola Brick Company's plant No. 1, with a capacity of 35,000 brick a day, is situated about a mile east of the town. It was installed in 1896, and manufactures principally common, or building, brick and sidewalk brick. Plant No. 2, installed in 1899, is located south of the town, on the north side of the mound which supplies shale to the Iola Portland-Cement Company's plant.

Its plant No. 1 (Pl. VIII, *A*) is the oldest plant at Iola, and was one of the first to employ gas for burning brick. It employs the up-draft or open-top kiln, with the tops temporarily closed for each charge. Gas is admitted to the side of the kiln as described for the Chanute plant. The shale is obtained near the plant by digging or mining; the soil covering is thin and the shale lies immediately below. The pit is operated to a depth of about 20 feet and is developed laterally as requirements demand. As the shale lies immediately on top of the Iola limestone it belongs to the Concreto series.

Plant No. 2 was established at the foot of a little mound south of town, because experience showed that shale could be mined more cheaply from a hillside, where no expense was necessary for draining the shale pit and where gravity could be used in transporting the shale from the pit to the plant, than on a level where the pit was worked downward and must be drained by pumping. The plant has a capacity of about 40,000 brick a day. Its general equipment, the kind of brick made, and methods of operations are in no essential way different from those at plant No. 1.

In 1899 the Star Brick Company established a plant at Iola, which has a capacity of 40,000 brick a day, and is located on the northeast corner of the mound which supplies the Iola Portland Cement Company with shale. It produces common building brick and sidewalk brick. The shale used is the same as that used by the Iola Brick Company in their plant No. 2.

The Home Brick Company's plant, located about 1½ miles east of Iola, began operations in June, 1902. The plant was built expressly to manufacture a high grade of pressed brick for fine buildings and has started out very successfully, supplying the brick for the new courthouse now in process of erection at Iola and already receiving a satisfactory patronage from outside sources; it also makes common building brick. Its total capacity is 30,000 brick for a 10-hours' run. It uses shale immediately at its plant, there being about 30 feet of the Concreto series there. It has its own gas wells near the plant and will drill more when the ones now in use are exhausted.

Brick plants at Laharpe.—Laharpe had one brick plant in operation and two others in process of construction during the summer of 1903. The plant in operation was installed in 1900 with a capacity of from 20,000 to 25,000 brick a day. Gas is the only fuel used, the motive power being steam generated by gas. The kilns are supplied with gas drawn through mains and fed into the kilns as at Chanute. The kilns used are of the ordinary up-draft variety. This plant makes common, or building, brick and sidewalk brick only. It obtains its shale by mining the Chanute shales from underneath the Iola limestone, having run an incline through about 35 feet of limestone; the shale is now being worked to a depth of 25 to 30 feet below the bottom of the limestone. In obtaining the shale by this method, it is necessary to mine it out so as to leave large pillars standing to support the roof. A room-and-pillar system like that in coal mining is employed. The entries and rooms, however, are very wide, as the overlying limestone is heavy and unusually free from vertical seams.

COAL, LEAD, AND ZINC.

COAL.

There are no workable beds of coal outcropping in the Iola quadrangle. Some beds have been found, but their thickness does not exceed 6 inches. In the Dudley shale on the northwest side of the limestone ridge, which terminates 3 miles northwest of Walnut, a thin coal bed was discovered in digging a well. On Coal Creek, 2 miles east of Humboldt, a bed of coal about 6 inches thick occurs in the Chanute shale. At a place where it was under very thin cover a small amount was obtained by stripping. The outcrop of this bed, or possibly of other beds which occupy the same horizon, has been noted at several places along Coal Creek, and small pieces are occasionally washed out of the shales during high water.

Some prospect wells have been sunk for coal, and others which have been bored in search of oil and gas show the occurrence of coal beds at a considerable depth, most of them in the Cherokee shale. No very reliable data in regard to their thickness are available, since they have usually been encountered in drilling with a churn drill. The record of a well sunk at St. Paul with a diamond drill shows several beds, the thickest of which is 2 feet; this was found at a depth of 184 feet, occupying a position immediately below the Pawnee limestone. In the Cherokee shale six beds of coal were reported, varying in thickness from 6 inches to 1½ feet. The Acers well at Iola, commonly known as the old mineral well, was drilled with a diamond drill in search of coal, but no information as to the coal beds encountered is available. Evidently none were found which were considered thick enough to work.

LEAD AND ZINC.

In digging wells which pass into or through the limestone formations, small amounts of lead and of zinc have occasionally been found. An occurrence of this character was observed in a well in the Shaw limestone just south of Savonburg. The lead and zinc, although conspicuous in the débris thrown out from the well, were not considerable in amount. Such occurrences of lead and zinc are very common in limestone formations, and may be considered sporadic and not indicating deposits of economic importance.

WATER SUPPLY.

In the Iola quadrangle the portion of the rainfall that is carried away by streams finds its way to the Mississippi either around the northern border of the Ozark region by way of the Missouri or to the south round the southern border by way of the Arkansas. The watershed between these two drainages is a low narrow divide, which extends from the foot of the Rocky Mountains near Denver, Colo., into southeast Missouri. It enters the Iola quadrangle west of Bayard and passes by the way of Moran to Elsmore and thence in a southeasterly direction. The streams which head to the east of the divide form the headwaters of the Little Osage and its tributary, the Marmaton. Practically all the remaining streams flow into Neosho River within the borders of the quadrangle.

Streams.—All of the streams here under discussion carry potable water. Neosho River is the largest. It enters the quadrangle at the northwest corner and flows nearly south along the west border of the area to Chanute, from which point it flows southeast, passing out of the quadrangle at about the middle of the south side. Its source is about 125 miles to the northwest in Morris County. As its hydrographic basin has an area of approximately 3,670 square miles and has an annual precipitation of 35 to 40 inches, it carries a large amount of water and consequently is a stream of great economic importance. Its average flow, as estimated by Mr. F. H. Newell,[a] based upon measurements made by W. G. Russell at Iola during 1902, is 2,492,041 acre-feet per annum. The flood plain averages about 2 miles in width, although in some places where heavy limestones are cut through its width is less than a mile. The stream meanders through the flood plain, producing many short oxbow curves and broad windings. In times of high water it overflows its banks and inundates almost all of the flood plain area, causing great destruction of crops and domestic animals and sometimes of human life. Along portions of the river dikes have been constructed to protect the bottom lands from overflow.

In the part of its course which lies in the Iola quadrangle, the Neosho has reached a graded condition and consequently there are no falls or cataracts along it and few and unimportant riffles or shoals. It is very serviceable as a supply of water for domestic uses. Iola and Chanute have city water plants which draw their supply from it and Humboldt contemplates the early installation of a similar plant.

A number of small streams enter the Neosho from the west, the largest of which are Owl Creek near Humboldt, Village and Turkey creeks near Chanute, and Elk Creek opposite Shaw. From the east it receives Elm Creek at Iola, Coal Creek at Humboldt, Big and Canville creeks near Shaw, Fourmile Creek near Erie, and Rock Creek near St. Paul.

The streams in the northeast part of the Iola quadrangle rise near the escarpment formed by the Bronson limestone. This section is more deeply dissected than the remaining portion of the quadrangle, the valley of the Marmaton, where it leaves the quadrangle, being 200 feet below the upland.

The only stream in the area under discussion large enough to furnish water power is the Neosho. A dam built across it at Iola has furnished power for a flouring mill and a sawmill. At Humboldt a dam has also been employed for running a flour mill and some small factories. Since the discovery of natural gas the use of this water power has been neglected to a great extent and there is little indication that it will ever be restored so long as the gas is abundant. The possibilities of water power along the Neosho are, however, worthy of notice. The stream has a fall of over 100 feet within the quadrangle, which amounts to about 3 feet per mile. At many places there are sites favorable for the construction of dams which might give a fall of from 12 to 15 feet. It is possible that some day the power which may be developed in this way will be used.

[a] Newell, F. H., Report of progress in stream measurements for the calendar year 1902; Water-Sup. and Irr. Paper, U. S. Geol. Survey, No. 84, 1903, p. 116.

Springs.—There are practically no prominent springs in the country under discussion. In many places, however, the seepage of water on hillsides and along the minor drainage courses where there is a considerable mantle of detrital material and soil makes possible what are called springs, although they are in reality of the nature of wells. Occasionally seeps are found which, during wet weather, furnish a small flow which is usually utilized as stock water. Nowhere are springs depended upon for domestic use, though the water supply is often denominated a spring by the inhabitants.

Wells.—Shallow wells formerly supplied water for domestic use. They were spring wells of the nature above described. Now that the country is practically all settled and it has become necessary to obtain water on the uplands where there are no small drainages, many deep wells have been dug or drilled. Good potable water is not readily found, since nearly everywhere the shales encountered in drilling contain soluble mineral matter which gives the water a brackish taste. Many wells are supplied by ground water which finds its way along the joints and bedding planes of the limestones, in which case it is of the quality spoken of as hard. In certain areas, however, the formations carry beds of sandstone (particularly in the belt of country occupied by the Chanute shale), from which water that is soft may sometimes be obtained. A few years since, efforts to obtain water which would not fail during unusually dry seasons led to the drilling of deep wells and developed the fact that where the sandstones in the Chanute shales can be reached at a moderate depth, a supply of good water is often available. By reference to the map it will be seen that this belt of country extends in a diagonal line through the quadrangle to the west of the line of outcrop of the formation. In the vicinity of Moran and Bronson the importance of this water-bearing horizon has been quite fully determined. In prospecting for water farther west these sandstones lie at a greater depth and the water found in them is usually more or less salty. An explanation of this may be found by studying the dip of the formations in the field in general; the rocks dip west and are known to extend for a long distance in that direction without a change of dip, their only outcrop being that in which they take in the water. Accordingly they become saturated, and having no outlet, the soluble salts in the rocks tend to become concentrated into a brine. The deep wells drilled in prospecting for oil and gas have shown that salt water is practically everywhere present in the rocks which lie at a considerable depth. The portions of the formations near the outcrop may be said to have been leached of their soluble salts, and accordingly it is only in these places that the water is fresh.

SOILS.

Origin of soils.—Soil is a mixture of fine-grained materials which have resulted from the disintegration and decomposition of rocks and which are mingled with a varying amount of organic material and with chemical substances derived from solution. The fragmental materials are derived from igneous or sedimentary rocks and may be redeposited and eventually form other sedimentary rocks. In the complete cycle soil represents a transitory stage. In the redeposition of rock materials, mechanical sorting gives rise to beds which are arenaceous (sandstones) or argillaceous (shales), according as the material that predominates is sandy or clayey. Rock materials which go into solution, such as salts of lime and magnesia, may be deposited in the soils by evaporation or precipitation, or, if these processes take place from bodies of water, may form sedimentary beds (limestones, dolomites, gypsum, etc.).

The principal classes of sedimentary rocks are (1) limestones and dolomites, (2) shales, and (3) sandstones. They, however, grade into each other, so that limestones are more or less shaly and sandy, shales are more or less limy and sandy, and sandstones are more or less shaly and limy. Limestones and dolomites, upon weathering, are largely carried away in solution. The argillaceous matter which they contain goes to form a clay soil, while the small fragments and the coarser pieces which result from weathering, as well as the included flints, form sands and gravels. Sandstones upon disintegration become sands and produce sandy soils, while shales give rise to clay soils.

Classification of soils.—In accordance with the foregoing discussion soils may be classified according to texture as gravelly, sandy, silty, and clayey. These classes may be recognized without mechanical analysis. Inasmuch as soil particles are, however, never of uniform size, soils may be more appropriately described by combining the textural terms; for example, we may speak of sandy clays, silty clays, sandy silts, etc.

According to their place of origin, soils may be classed as (1) sedentary, (2) migratory, and (3) transported. Sedentary soils are those which are derived by disintegration and decomposition of rocks in place, the materials which are removed in the formation of the soil being carried away in solution. Migratory soils are those which are shifting from their place of origin and are moving with the slope of the surface, largely as a result of gravitative action. The area occupied by them is usually connected with their place of origin. Transported soils consist of materials which have been moved by the action of water, ice, or wind. They may accordingly be considered under the subclasses of alluvial, glacial, and eolian soils.

Soils of the Iola quadrangle.—The area here under discussion has not been subjected to glacial action and there are no important accumulations of wind-blown materials. Along Neosho River and some of the larger creeks, however, there are transported soils which are alluvial. Neosho River, which is the only important stream entering the area, traverses in its upper course a belt of country occupied by sedimentary rocks. The materials which it transports are accordingly sands, clays, and gravels derived from limestones, sandstones, and shale beds. Except for the assorting of these materials and the commingling with them of a larger amount of organic matter the alluvial deposits do not differ from those found along the creeks that lie within the Iola quadrangle. The alluvium along Neosho River is seldom more than 2 miles wide, and in places its area is so constricted as a result of the rock walls which limit its flood plain that it is little more than a mile in width. Within the alluvium are occasional beds of gravel and sand, but its surface is principally covered with fine silts. Along Rock, Canville, Big, and Elm creeks, as well as on certain smaller streams, are narrow areas in which flood-plain deposits are formed, the material being derived from the drainage basins of the streams.

On the uplands the soils are in part residual and in part migratory. The rocks, as will be seen by reference to the geologic map, are shales and sandstones alternating with limestones. The topography is of the indistinct terrace and escarpment type. The soils lying on the terraces have resulted largely from the disintegration of rocks in place, while at the base of the escarpments and on the more decided slopes the soils are migratory.

It is not possible to show in this discussion the types of soils which would be distinguished in a soil survey. However, the limestones, sandstones, and shales have each contributed to the soils, and accordingly we find clays, gravels, and sands, which in many cases may be traced directly to the beds that have given rise to them through disintegration. The gravels have been formed by the weathering out of the flints found in the limestones, especially in the Bronson and its equivalents, the Hertha, Dennis, and Drum limestones, and in a minor degree in the Parsons, Iola, Allen, and Piqua. Most of the limestones contain but little argillaceous and arenaceous material. The calcareous portion goes into solution and is redeposited by evaporation and precipitation, so that in many places the lime content of the soil is large.

The sandstone and shale formations vary in character and lateral extent with individual beds. The Chanute shales are particularly sandy as compared with the other formations, but the soil derived from them shows a larger percentage of sand than the rocks themselves, since the sand is not so readily transported as the clay and forms surface accumulations. The soils from the remaining shale beds are largely clay soils.

The thickness of the soil is important as determining its agricultural value, and is related in large measure to the geologic formations and the structure of the rocks. In the areas occupied by the limestones weathering produces dip slopes on the upper surface of the limestone beds, and the migration of the soils and their transportation by running water are apt to reduce the residual material to a thin mantle. Accordingly in dry seasons these thin soils do not produce well, since they do not retain sufficient moisture.

The character of the soils has a certain influence upon the distribution of the trees. The Chanute shales, which have been described as giving rise to sandy soils, support a considerable growth of black jack (*Quercus nigra*), a species that originally covered the larger areas which are otherwise prairie lands, and that still constitutes the principal timber growth on the uplands. The alluvial soils along Neosho River and the larger creeks support a mixed growth of hard woods.

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PUBLICATIONS OF UNITED STATES GEOLOGICAL SURVEY.

[Bulletin No. 238.]

The serial publications of the United States Geological Survey consist of (1) Annual Reports, (2) Monographs, (3) Professional Papers, (4) Bulletins, (5) Mineral Resources, (6) Water-Supply and Irrigation Papers, (7) Topographic Atlas of United States—folios and separate sheets thereof, (8) Geologic Atlas of United States—folios thereof. The classes numbered 2, 7, and 8 are sold at cost of publication; the others are distributed free. A circular giving complete lists may be had on application.

The Professional Papers, Bulletins, and Water-Supply Papers treat of a variety of subjects, and the total number issued is large. They have therefore been classified into the following series: A, Economic geology; B, Descriptive geology; C, Systematic geology and paleontology; D, Petrography and mineralogy; E, Chemistry and physics; F, Geography; G, Miscellaneous; H, Forestry; I, Irrigation; J, Water storage; K, Pumping water; L, Quality of water; M, General hydrographic investigations; N, Water power; O, Underground waters; P, Hydrographic progress reports. This bulletin is the thirty-eighth in Series A and the forty-fourth in Series B, the complete lists of which follow. (PP = Professional Paper; B = Bulletin.)

SERIES A, ECONOMIC GEOLOGY.

B 21. Lignites of Great Sioux Reservation: Report on region between Grand and Moreau rivers, Dakota, by Bailey Willis. 1885. 16 pp., 5 pls. (Out of stock.)

B 46. Nature and origin of deposits of phosphate of lime, by R. A. F. Penrose, jr., with introduction by N. S. Shaler. 1888. 143 pp. (Out of stock.)

B 65. Stratigraphy of the bituminous coal field of Pennsylvania, Ohio, and West Virginia, by I. C. White. 1891. 212 pp., 11 pls. (Out of stock.)

B 111. Geology of Big Stone Gap coal field of Virginia and Kentucky, by M. R. Campbell. 1893. 106 pp., 6 pls.

B 132. The disseminated lead ores of southeastern Missouri, by Arthur Winslow. 1896. 31 pp.

B 138. Artesian-well prospects in Atlantic Coastal Plain region, by N. H. Darton. 1896. 228 pp., 19 pls. (Out of stock.)

B 139. Geology of Castle Mountain mining district, Montana, by W. H. Weed and L. V. Pirsson. 1896. 164 pp., 17 pls.

B 143. Bibliography of clays and the ceramic arts, by J. C. Branner. 1896. 114 pp.

B 164. Reconnaissance on the Rio Grande coal fields of Texas, by T. W. Vaughan, including a report on igneous rocks from the San Carlos coal field, by E. C. E. Lord. 1900. 100 pp., 11 pls.

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B 182. A report on the economic geology of the Silverton quadrangle, Colorado, by F. L. Ransome. 1901. 266 pp., 16 pls.

B 184. Oil and gas fields of the western interior and northern Texas Coal Measures and of the Upper Cretaceous and Tertiary of the western Gulf coast, by G. I. Adams. 1901. 64 pp., 10 pls. (Out of stock.)

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PP 1. Preliminary report on the Ketchikan mining district, Alaska, with an introductory sketch of the geology of southeastern Alaska, by Alfred Hulse Brooks. 1902. 120 pp., 2 pls.

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DEPARTMENT OF THE INTERIOR

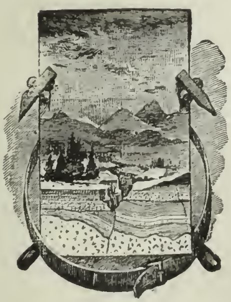
UNITED STATES GEOLOGICAL SURVEY

CHARLES D. WALCOTT, Director

ROCK CLEAVAGE

BY

CHARLES KENNETH LEITH



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Department of the Interior,
United States Geological Survey,
Washington, D. C., May 17, 1904.

Sir: I have the honor to transmit herewith the manuscript of a paper on rock cleavage, by Charles Kenneth Leith, and to recommend its publication as a bulletin.

The paper embodies the results of a very careful and laborious investigation of facts concerning rock cleavage and a discussion of their theoretical significance. Its publication will place the subject of rock cleavage in a much more satisfactory shape and be of material assistance to all structural geologists.

Very respectfully,

C. W. Hayes,
Geologist in Charge of Geology.

Hon. Charles D. Walcott,
Director United States Geological Survey.

ROCK CLEAVAGE.

By Charles Kenneth Leith.

INTRODUCTION.

DEFINITION OF CLEAVAGE.

Rock cleavage, as commonly defined in geological text-books, in effect, is a rock structure by virtue of which the rock has the capacity to part along certain parallel surfaces more easily than along others. It is possessed by a considerable proportion of the rocks of the lithosphere. It is usually distinguished from actual partings of a similar nature. The parallel structures may be original or secondary.

(1) Original structures are induced in the rock mainly during its solidification from a magma or deposition in water, though perhaps modified by subsequent static metamorphism. They comprise sedimentary bedding, flow structure of lavas, certain gneissic structures, and pegmatite structures.

(2) Secondary structures are induced by deformation through metamorphic processes subsequent to the formation of the rock. They have been given various names, such as cleavage, slatiness, schistosity, foliation, fissility, etc.

Generally, the secondary structure only has been considered under cleavage, but it is apparent that there is nothing in the definition of the term, rock cleavage, as above given, to prevent its application to any of these structures, whether original or secondary. It was so applied by Le Conte.[a] The writer believes that the facts presented in this paper will justify the conclusion that there is no essential difference between the original and the secondary structures; that in some cases they are not to be discriminated with certainty, and that both should be included under rock cleavage. Therefore, the term cleavage will be used as above defined; it will be confined to structure, and will have no significance as to origin. Where the

[a] Says Le Conte: "This structure is usually treated under metamorphic rocks, as a kind of metamorphism; but it is found in rocks which have not undergone ordinary metamorphic changes, and it is produced by an entirely different cause." Le Conte, J., Elements of Geology, 4th ed., 1896, p. 189.

origin of the structure is clear the term original, or secondary, may be prefixed.

The application of terms pertaining to cleavage, as here used, is summarized in the following table:

- *Rock cleavage.* (Cleavable rock.)
  - *Original cleavage.* (Protoclase or original-cleavage rock.)
    - Bedding.
    - Flow structure in lavas.
    - Parallel structure in certain gneisses.
    - Pegmatitic structure.
    - Parallel structure due to the arrangement of feldspars in certain gabbros, etc.
  - *Secondary cleavage.* (Metaclase or secondary-cleavage rock.)
    - *Flow cleavage.* Including in whole or in part: "Ultimate cleavage" of Sorby, "Cleavage" of most writers, "Slaty cleavage," "Cleavage proper," etc.
      - Schistosity. (Schists.)
      - Slatiness. (Slates.)
      - Parallel structure in certain gneisses. (Comes partly under schistosity.)
    - *Fracture cleavage.* Including in whole or in part:
      - Close joints cleavage.
      - False cleavage.
      - Strain slip cleavage.
      - Slip cleavage.
      - Ausweichungs cleavage.
      - Fissility in part. (The term is retained for closely spaced parallel partings.)
      - Rift.

In this classification several new terms required for the systematic classification of cleavage structures and cleavable rocks have been introduced. *Protoclase* may be defined as a rock possessing a cleavage originally developed during sedimentation under water or cooling from magma, such as bedding, flow structure, etc. *Metaclase* may be defined as a rock possessing a cleavage secondarily developed during rock deformation. Secondary cleavage is considered under the heads of *fracture cleavage* and *flow cleavage*. *Fracture cleavage* is conditioned by the existence of incipient, cemented, or welded parallel fractures, and is independent of a parallel arrangement of the mineral constituents. *Flow cleavage* is conditioned solely by a parallel arrangement of the mineral constituents. Fracture cleavage is a phenomenon of the zone of fracture, and flow cleavage of the zone of rock flowage. The structures are correlative, just as jointing and folding are correlative. The fitness of these terms will not be argued here, but it is hoped that it will appear from the following discussion.

IMPORTANCE OF METACLASIC STRUCTURE OR SECONDARY ROCK CLEAVAGE.

Secondary rock cleavage is found wherever rocks have been much deformed under conditions of rock flowage, and especially in mountainous areas and regions of ancient crystalline rocks. The correct interpretation of the structure throws light on the nature of rock deformation in general and its relation to the stresses producing it, and hence is of fundamental significance in determining the nature of mountain-making movements and stresses. Since so large a proportion of the rocks of the lithosphere develop this peculiar structure in adjusting themselves to the earth's stresses, there is warrant for the attempt to determine the true nature of the structure and the reason for its occurrence.

LITERATURE ON SECONDARY ROCK CLEAVAGE.

The literature on secondary rock cleavage is voluminous, but the conclusions thus far reached are so diverse that the geologist is still in doubt as to the true explanation of the phenomenon. An attempt is made below to outline the well-known hypotheses and to indicate what points are still under controversy.

The English geologists seem to have been the first to seriously attempt the explanation of secondary rock cleavage. Among them Sedgwick[a] should receive the first mention. His theory (proposed in 1829), that cleavage is due to the parallel arrangement of individual particles making up the rock mass, caused by "crystalline or polar" forces acting on the whole mass "simultaneously in given directions" and "with adequate power," was long and widely accepted. In 1838 Fox[b] published an account of the development of cleavage in clay used in the separation of copper and zinc in an electric battery. Because of the work of Sedgwick and Fox, cleavage was usually explained in the first half of the last century as due to "crystalline," "polar," or "magnetic" forces, terms evidently carrying somewhat vague meanings and well illustrating the state of knowledge on the subject at that time.

About the middle of the last century there appeared notable contributions to the subject by Darwin,[c] Dana,[d] Sharpe,[e] Sorby,[f] Tyndall,[g]

[a] Sedgwick, Adam, Remarks on the structure of large mineral masses, and especially on the chemical changes produced in the aggregation of stratified rocks during different periods after their depositions: Trans. Geol. Soc. London, 2d ser., vol. 3, pt. 1, 1835, pp. 461–486.

[b] Fox, R. W., On the lamination of clay by electricity: Edinburgh New Philos. Jour., old ser., vol. 25, 1838, pp. 196–198.

[c] Darwin, Charles, Geological Observations on South America during Years 1832–1836, pp. 161–168. Published in 1846.

[d] Dana, J. D., Silliman's Am. Jour., 1st ser., vol. 45, 1843, pp. 107–108.

[e] Sharpe, Daniel, On slaty cleavage: Quart. Jour. Geol. Soc., vol. 3, 1847, pp. 74–105, and vol. 5, 1849, pp. 111–129. On the arrangement of the foliation and cleavage of the rocks of the north of Scotland: Philos. Trans. Royal Soc. for 1852, 1852, pp. 445–461. Contains references to early work by De la Beche, Austin, Hunt, Murchison, and others.

[f] Sorby, H. C., Edinburgh New Philos. Jour., old ser., vol. 55, 1853, pp. 137–148; ibid., new ser., vol. 4, 1856, p. 339 et seq.; ibid., vol. 6, 1857, p. 316 et seq.; Philos. Mag., 4th ser., vol. 11, 1856, pp. 20–36; ibid., vol. 12, 1856, pp. 127–128; Quart. Jour. Geol. Soc. for Nov., 1863, pp. 401–406.

[g] Tyndall, John, Comparative view of the cleavage of crystals and slate rocks: Philos. Mag., 4th ser., vol. 12, 1856, pp. 35–47, 129–135.

and Phillips.[a] All subsequent contributions have contained in whole or in part the essential conclusions of these men. Among those who have added to or modified the theories of rock cleavage proposed by the scientists above named, the following should be particularly mentioned: King,[b] Daubrée,[c] Harker,[d] Becker,[e] Van Hise,[f] Hoskins,[g] and Adams and Nicolson.[h] Many other names might well be included, such as Dale,[i] Hutchings,[j] and Reade and Holland,[k] but the men named have suggested, emphasized, or modified some particular feature of the subject, and a discussion of their conclusions will indicate with a fair degree of clearness the present state of knowledge of the subject, and will obviate a tedious bibliographical discussion.

SECONDARY CLEAVAGE IN ITS RELATION TO A PARALLEL ARRANGEMENT OF MINERAL CONSTITUENTS.

All the writers above named, except Tyndall, King, Daubrée, and Becker, have assumed rock cleavage to be for the most part dependent on a parallel arrangement of the greatest, mean, and least dimensions of the mineral particles of unequal dimensions making up the rock mass. Sorby[l] was the first to maintain that the best cleavage exists in rocks which contain minerals "whose length and thickness differ most." Dana[m] and Van Hise[n] have in addition proposed and amplified the idea that the mineral cleavage of the parallel-arranged particles

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[a] Phillips, John, Report on cleavage and foliation in rocks, and on the theoretical explanation of these phenomena (pt. 1): Rept. 26th Meeting Brit. Assoc. Adv. Sci., held 1856, pp. 369-396. Published in 1857.

[b] King, W., On the structure of rocks called jointing: Trans. Royal Irish Acad., vol. 25, 1875, pp. 605-662.

[c] Daubrée, A., Géologie expérimentale, vol. 1, 1879, pp. 407-418.

[d] Harker, A., On slaty cleavage and allied rock structures, with special reference to the mechanical theories of their origin: Rept. 55th Meeting Brit. Assoc. Adv. Sci., held 1885, published in 1886, pp. 813-852. Contains bibliography.

[e] Becker, G. F., Finite homogeneous strain, flow, and rupture of rocks: Bull. Geol. Soc. America, vol. 4, 1893, pp. 13-90. Schistosity and slaty cleavage: Jour. Geol., vol. 4, 1896, pp. 429-448. Experiments on schistosity and slaty cleavage: Bull. U. S. Geol. Survey No. 241, 1904, 32 pp.

[f] Van Hise, C. R., Principles of North American pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 633-668. Deformation of rocks, pt. 3, Cleavage and fissility: Jour. Geol., vol. 4, 1896, pp. 449-483. Metamorphism of rocks and rock flowage: Bull. Geol. Soc. America, vol. 9, 1898, pp. 269-328. A treatise on metamorphism: Mon. U. S. Geol. Survey, vol. 47, 1904, pp. 748-763.

[g] Hoskins, L. M., Flow and fracture of rocks as related to structure: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 845-874.

[h] Adams, F. D., and Nicolson, J. T., An experimental investigation into the flowage of marble: Philos. Trans. Royal Soc. London, ser. A, vol. 195, 1900, pp. 363-401.

[i] Dale, T. N., The slate belt of eastern New York and western Vermont: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 3, 1899, pp. 163-307. Contains bibliography. Structural details in the Green Mountain region and in eastern New York: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 549-570.

[j] Hutchings, W. M., Clays, shales, and slates: Geol. Mag., new ser., dec. 4, vol. 3, 1896, pp. 309-317, 343-350.

[k] Reade, T. M., and Holland, Philip, The green slates of the Lake district, with a theory of slate structure and slaty cleavage: Proc. Liverpool Geol. Soc., 1900-1901, pp. 101-127. The phyllades of the Ardennes compared with the slates of North Wales: Proc. Liverpool Geol. Soc., pt. 1, 1897-98, pp. 274-293, and pt. 2, 1899-1900, pp. 463-478.

[l] Philos. Mag., vol. 12, 1856, p. 128.

[m] Loc. cit., p. 107.

[n] Jour. Geol., vol. 4, 1896, p. 453.

may aid in giving a secondary rock cleavage. Dana's conclusion is expressed in the words, "Modern igneous rocks are laminated, and in general more or less so according to the quantity and cleavability of the cleavable minerals they contain. Mica, the most perfectly foliated mineral, produces, when abundant and not overruled by other constituents, the most perfectly laminated rock." Van Hise has concluded that "rock cleavage is due to the arrangement of the mineral particles with their longer diameters or readiest cleavage, or both, in a common direction."

On the other hand, Tyndall[a] and Daubrée[b] performed experiments from which they concluded that secondary rock cleavage is independent of any parallel arrangement of the constituent particles. King[c] also maintained that cleavage, while perhaps in part due to a flaky or dimensional arrangement of the mineral constituents, "is essentially the result of pressure exerted against divisional planes, chiefly belonging to jointing, that existed in any given rock prior to its becoming affected by such pressure." Becker,[d] largely from a mathematical and experimental analysis of the relations of cleavage to pressure, later reached the conclusion that cleavage is essentially independent of any parallel arrangement of the mineral constituents, although such parallel arrangement may be present as an incidental result of the development of cleavage.[e]

MANNER IN WHICH A PARALLEL ARRANGEMENT OF MINERAL CONSTITUENTS IS BROUGHT ABOUT.

Those who maintain that the parallel arrangement of minerals is an essential condition for secondary rock cleavage differ among themselves as to the manner in which this arrangement is brought about. Sedgwick and Fox, followed by others, referred the parallel arrange-

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[a] Philos. Mag., vol. 12, 1856, p. 37.

[b] Géologie expérimentale, vol. 1, 1879, p. 413.

[c] Trans. Royal Irish Acad., vol. 25, 1875, p. 657.

[d] Bull. Geol. Soc. America, vol. 4, 1893, pp. 79, 80.

[e] Becker summarizes his view as follows (Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 3, p. 206): "Slaty cleavage is produced when a solid but plastic mass, firmly supported on one side, experiences a pressure on the opposite side which is not perpendicular to the supporting surface. The resulting cleavage has a direction intermediate between that of the applied force and the fixed support. The cleavage itself makes with the deforming force an angle which may vary between a very small value and one equaling or even exceeding 45°. The firm support of the deformed rock required by the theory may be afforded either by a purely material resistance or by any combination of forces which prevents the mass from rotating as a whole while undergoing deformation. Lateral pressures not equal in all directions appear to be of minor importance so long as they do not interfere with the condition that the angle between the resultant force and the fixed support shall differ sensibly from 90°. The origin of the cleavage as conceived in this theory is incipient "solid flow," which is a different thing from liquid flow. The production of cleavage should usually be accompanied by the formation of master joints at angles to the cleavage approaching 90°, and the direction of the pressure is perpendicular to the intersection of the cleavage with such joints, intersecting (but not exactly bisecting) the obtuse angle. The grain of the slate should be parallel to this intersection. In general there should be an elongation in the direction of the grain and a contraction in the plane of cleavage at right angles to the grain."

See also Becker, G. F., Experiments on schistosity and slaty cleavage: Bull. U. S. Geol. Survey No. 241, 1904.

ment to "crystalline," "polar," or "galvanic" forces. Darwin[a] supposed the arrangement to have been induced by "tension," "before the final consolidation of the mass and the total cessation of molecular movement." Sorby[b] assumed the previous existence of flat particles and supposed their arrangement to be due to rotation during the secondary deformation of a rock by shortening of the rock mass in one direction and elongation in a perpendicular direction, but he concluded also that other particles may have been flattened in situ, and that some of the parallel flat particles are secondary developments, particularly in "schists," which he distinguished from "slates." Sharpe[c] supposed every particle in a deformed rock to have taken part in the elongation and shortening which the rock underwent, thus accounting both for the flatness of the particles and for their parallel arrangement. Sharpe[d] concluded also that, while "no connection has been detected between cleavage and crystallization beyond the tendency of mica and talc to arrange themselves along the planes of cleavage," still on these planes "there would be the least resistance to their intrusion or formation" and the development of such minerals "may have been a subsequent operation." Van Hise[e] believes the causes of the parallel arrangement conditioning rock cleavage to be, first and of most importance, the parallel development of new minerals; second, the flattening and parallel rotation of old and new mineral particles; and third and of least importance, the rotation into approximately parallel positions of particles which had originally a random arrangement. Van Hise thus differs from Sorby in maintaining the predominance of the new development of minerals, which was suggested by Sorby only as a minor detail. Adams and Nicolson deformed limestone at temperatures of 300° and 400° C., and obtained a flattening of calcite particles, and thus a parallel structure, through twinning and gliding, a movement which occurs also in the deformation of metals and ice. At ordinary temperatures the flattening produced in this way was associated with actual granulation of the particles. Comparing the results of experiments with the deformation observed in marbles in the field, they concluded that while "recrystallization undoubtedly plays an important, and in many cases probably a chief, part in the great movements which are observed to have taken place in the limestones of contorted districts, this process is by no means the only one by which such movements are brought about."[f] They may be brought about by the development of cataclastic structure and through gliding and twinning of the constit-

[a] Philos. Mag., vol. 12, 1856, p. 168.

[b] Edinburgh New Philos. Jour., vol. 55, 1853, pp. 137–148. Quart. Jour. Geol. Soc., vol. 19, 1863, pp. 401–406.

[c] Quart. Jour. Geol. Soc., vol. 3, 1847, p. 74–105.

[d] Quart. Jour. Geol. Soc., vol. 5, 1849, p. 129.

[e] Jour. Geol., vol. 4, 1896, p. 453. Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, p. 635.

[f] Philos. Trans. Royal Soc. London, ser. A, vol. 195, 1900, p. 398.

uent crystal particles. The latter processes give a parallel arrangement of the particles. They concluded further that the "flowage of the granite and other harder crystalline rocks" (and, presumably, a parallel arrangement of the deformed particles) might be induced in much the same way.[a]

The processes resulting in the deformation of rock masses have been discussed by many other writers,[b] who do not emphasize the development of parallel arrangement of mineral particles, resulting from the deformation.

TWO STRUCTURES INCLUDED UNDER CLEAVAGE, ONE OF THEM NOT DEPENDENT UPON A PARALLEL ARRANGEMENT OF MINERAL CONSTITUENTS.

Sorby,[c] in 1857, showed that cleavage properly included two distinct phenomena, a capacity to part along incipient parallel fractures independent of any parallel arrangement of the minerals, and a capacity to part parallel to, and conditioned by, the parallel arrangement of the mineral constituents. The first he called "close-joints cleavage," and the second "ultimate structure cleavage." A similar view was held in 1878 by Professor Heim,[d] who discriminated an "ausweichungs cleavage" which results from a succession of small displacements or faults, usually in connection with overfolds, and independent of any parallel arrangement of mineral constituents, from another cleavage called in part "micro-cleavage," which is dependent for its existence on the parallel arrangement of the mineral constituents. Harker,[e] in 1886, used the term cleavage "in a sense sufficiently wide to include not only the structure discussed under the name slaty cleavage proper, but also other structures, which though effectively identical with it have been produced in a different manner;" that is, in the manner described by Sorby and Heim for their "close joints" and "ausweichungs" cleavage. Van Hise[f] in 1896 distinguished *cleavage* or capacity to part, dependent on a parallel arrangement of the mineral constituents, from *fissility*, "a structure in some rocks by virtue of which they are already separated in parallel laminae in a state of nature," and do not necessarily require a parallel arrangement of the mineral constituents, although this is usually developed in rocks showing this structure. As thus defined, fissility is a phenomenon quite separate and distinct from cleavage. But Van Hise in a subsequent discussion used the term fissility also for rocks in which the

[a] Adams, F. D., and Nicolson, J. T., An experimental investigation into the flowage of marble: Philos. Trans. Royal Soc. London, ser. A., vol. 195, 1900, p. 399.

[b] See excellent summary by Adams, op. cit.

[c] Rept. 27th Meeting Brit. Assoc. Adv. Sci., held 1857, p. 92. Published in 1858.

[d] Uber den Mechanismus der Gebirgsbildung, vol. 2, 1878, pp. 51–58.

[e] Rept. 55th Meeting Brit. Assoc. Adv. Sci., held 1885, p. 836. Published in 1886. Contains bibliography.

[f] Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, p. 633. Jour. Geol., vol. 4, 1896, pp. 449–450.

parallel fractures are incipient or have been cemented or welded, giving the rock a capacity to part, or cleavage, rather than an actual parting. Other terms which have been used for cleavage developed in this manner are rift, fault-slip cleavage, slip cleavage, and false cleavage.

FALSE CLEAVAGE.

"False cleavage," or "grain," or "bate cleavage," normal to cleavage proper, was noted by several of the early observers, Sedgwick,[a] Phillips,[b] and De la Beche,[c] and by many later investigators. Sharpe and many following him have concluded that the structure is due to breaking along the greater or mean axes of the mineral particles arranged parallel, but others have held that the structure is due to obscure divisional planes developed in the manner of fracture cleavage.

CLEAVAGE IN ITS RELATIONS TO DIRECTION OF APPLICATION OF THE PRESSURE PRODUCING IT.

Concerning the relations of secondary cleavage or parallel arrangement of minerals, or both, to pressure, there is again considerable difference in the views held. Sharpe,[d] Sorby,[e] and Tyndall[f] held that cleavage develops in planes normal to the greatest pressure, the two latter having produced it in such planes experimentally. Sharpe supposed also that heat and "galvanism" may have helped pressure, and Sorby admitted the existence of another cleavage structure, his "close-joints cleavage," presumably developed with inclination to the pressure in the manner of joints. King argued that slaty cleavage is the result of "pressure exerted against divisional planes, chiefly belonging to jointing, that existed in any given rock prior to its becoming affected by such pressure,"[g] the preexisting divisional planes having developed in planes inclined to the greatest compression in a manner common to jointing structures. Daubrée[h] produced cleavage parallel to the direction of flow by forcing plastic clay through a cylinder. Becker,[i] in 1893 and 1904, maintained on mathematical grounds that slaty cleavage is developed along planes inclined to the greatest pressure. In

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[a] Synopsis Classification British Paleozoic Rocks, London, 1854, p. xxxv.

[b] Phillips, John, On a group of slate rocks ranging east-southeast between the rivers Lune and Wharfe, from near Kirby Lonsdale to near Malham, and on the attendant phenomena: Trans. Geol. Soc. London, 2d ser., vol. 3, pt. 1, 1829, pp. 1–19.

[c] Geol. Observer, 2d ed., 1853, p. 588, fig. 239.

[d] Quart. Jour. Geol. Soc., vol. 3, 1847, p. 75.

[e] Philos. Mag., vol. 11, 1856, p. 26.

[f] Philos. Mag., vol. 12, 1856, p. 37.

[g] Trans. Royal Irish Acad., vol. 25, 1875, p. 657.

[h] Géologie expérimentale, vol. 1, 1879, p. 413.

[i] Becker, G. F., Finite homogeneous strain, flow, and rupture of rocks: Bull. Geol. Soc. America, vol. 4, 1893, pp. 13–90. Experiments on schistosity and slaty cleavage: Bull. U. S. Geol. Survey No. 241, 1904.

1896 Van Hise and Hoskins[a] held that cleavage, during deformation, develops at any instant in planes normal to the greatest pressure, but that the final direction of cleavage may be inclined to the direction of greatest pressure which has produced the deformation. This conclusion was based on field observations by Van Hise and on mathematical analysis by Hoskins. Their "fissility," corresponding essentially with Sorby's "close-joints cleavage," develops, they maintain, in the manner of fractures in shearing planes inclined to the greatest pressure.

PURPOSE OF PRESENT PAPER.

It will be fundamentally assumed that secondary rock cleavage is of two kinds, which differ widely in their essential causes and conditions. Abundant evidence of the truth of the assumption appears, it is believed, in the facts here recorded. The cleavage developing during rock flowage (or the deformation of rock without conspicuous fracture) will be called *flow cleavage*, and that developing through the deformation of rock by fracture and subsequent cementation will be called *fracture cleavage.*

In distinguishing the two kinds of cleavage the writer is in essential accord with Sorby, Heim, Harker, Van Hise (if his fissility be in part called cleavage), and others. The term fissility is retained for closely spaced parallel partings as defined by Van Hise, but is not extended to include the capacity to part fractures, which is properly a cleavage, and is here called fracture cleavage.

One of the principal causes of confusion in the discussion of cleavage has been the attempt by some authors to make the explanation of one kind of cleavage apply to all cleavage. On the one hand, the parallel arrangement of mineral constituents has been held to be essential to all cleavage, and, on the other, the parallel fractures independent of any arrangement have been strongly urged as sufficient cause for all cleavage.[b] An attempt will be made to show that each of these explanations is adequate for one kind of cleavage, but not for all cleavage. Especial emphasis will be placed on the proof that incipient or cemented parallel fractures, yielding what is here called fracture cleavage, will not explain what is here called flow cleavage, or cleavage dependent upon the parallel arrangement of the mineral constituents. This will require detailed discussion of the internal arrangement of the mineral constituents of rocks with each kind of cleavage, the relations of this arrangement to the observed cleavage, the nature of the processes bringing about the arrangement, and the relations of the arrangement to pressure. Especial attention will be paid to the causes and conditions of flow cleavage, which is the most characteristic structure in rocks ordinarily considered cleavable.

[a] Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, p. 638. Jour. Geol., vol. 4, 1896, p. 157.
[b] Becker, G. F., Experiments on schistosity and slaty cleavage: Bull. U. S. Geol. Survey No. 241, 1904.

The prevailing differences of opinion concerning the relations of cleavage to the arrangement of mineral particles, the processes bringing about the arrangement, and even the relations of cleavage to pressure, may be traced in part to vague and incomplete knowledge of the intimate nature of cleavage itself. Students of the subject have made numerous careful observations, but with a few exceptions have confined their observations to one aspect of the subject. There is thus a need of systematic microscopical study of cleavage of rocks of all kinds from many localities, with a definite purpose of ascertaining the exact arrangement of the mineral particles, the relations of the observed arrangement to cleavage, and the relations of cleavage to the deformation of rocks. The present investigation has attempted to supply in some degree this observational deficiency. With the basis of observed fact thus obtained it is possible to present with some degree of confidence certain general conclusions as to the origin and conditions of cleavage.

The phenomena of flow cleavage will be treated in Part I. Part II will be devoted to fracture cleavage, and a comparison of fracture cleavage and flow cleavage. Original cleavage of bedding, flow structure, etc., will be treated independently in Part III.

MATERIAL USED IN INVESTIGATION.

The material studied has been drawn from the rock collection of the section of pre-Cambrian and metamorphic geology of the United States Geological Survey, numbering 40,000 specimens and upward of 15,000 thin sections, representative of the principal crystalline schist areas of North America; from the metamorphic rocks belonging to the Wisconsin Geological Survey; and from the University of Wisconsin collection of metamorphic crystalline rocks from various parts of North America and Europe, including specimens of most of the well-known metamorphic cleavable rocks of both continents. From the Survey and university material a large number of typical specimens and slides were selected for special study. Where any feature was especially well exhibited in the slide, or where the slide had been cut in planes indeterminate with reference to the rock cleavage, new sections were cut, usually in three mutually perpendicular directions, with known relations to cleavage. Perhaps 1,000 specimens and slides were selected for close study, and of these 250 slides were specially prepared. In addition to the metamorphic crystalline rocks, a considerable number of semicrystalline and partly consolidated sediments in the same collections were examined. Finally several specimens and slides of typical cleavable rocks from various parts of North America were loaned by men who had collected and studied them. It is believed that the conclusions as to the causes and conditions of rock cleavage, which are based on the study of the great variety of cleavable rocks available from widely separated localities, will apply to cleavable rocks in general. It is inevitable, however, that certain phenomena are more apparent than others in the particular slides examined, and thus that these phenomena will be overemphasized in the following discussion and others will receive less attention than they should. Further work will doubtless show modification of emphasis to be necessary.

Illustrative specimens and slides are cited in the text. Where no letters are attached the numbers refer to the collection of the section of pre-Cambrian and metamorphic geology of the United States Geological Survey. The letter W. with a number signifies Wisconsin Geological Survey, U. W., University of Wisconsin, H., Hobbs, and C., Clements.

EXPERIMENTAL WORK.

This report, in substantially the present form, was submitted for publication in the spring of 1903, and was referred to a committee consisting of Messrs. Whitman Cross and George F. Becker. On the recommendation of Doctor Becker, publication was postponed until he and the writer might jointly perform experiments, which had been planned by Doctor Becker, on the artificial development of cleavage. In December, 1903, a few days were spent on these experiments in the chemical and physical laboratory of the United States Geological Survey at Washington. It was planned to continue the experiments at a subsequent date, but opportunity did not recur. The results, which were not decisive, are referred to on pages 126–130. So far as they were carried, the experiments did not seem to the writer to require a modification of the views here stated. Further, so largely is the present report a record of observed facts of cleavage produced by nature, with only such general conclusions as would obviously follow, that it is not thought likely that further experimental work would require essential modification, although it would doubtless make possible a more definite and mathematical treatment of the subject and aid in the interpretation of the facts observed.[a]

ACKNOWLEDGMENT.

The investigation here reported upon was undertaken at the suggestion of Dr. C. R. Van Hise, was carried on under his supervision, and the results reviewed by him. The paper, as it stands, is in considerable part an expression—amplified, modified, and accompanied by

[a] While the above paragraph was in proof, the writer received a report by Doctor Becker on Experiments on schistosity and slaty cleavage (Bull. U. S. Geol. Survey No. 241, 1904), which covers the experimental work above referred to, as well as work previously and subsequently done by Doctor Becker. The conclusions reached are essentially the same as in Doctor Becker's previous papers (cited p. 14), in which, as it seems to the writer, the attempt has been made to apply one explanation to two distinct cleavage phenomena. Doctor Becker's conclusions are, as he states, "founded on experiment and analysis." He does not attempt to describe the facts as shown by the rocks themselves. His method is deductive. The writer's point of view is almost altogether different. He has attempted, after the inductive method, to study the facts in the field and laboratory and to point out their significance.

detailed proof—of general ideas which he had obtained from his own observations on rock cleavage. For this material aid, as well as for unusual facilities for study, the writer is pleased to acknowledge his indebtedness to Doctor Van Hise.

Thanks are due Prof. L. M. Hoskins, of Leland Stanford Junior University, and Prof. E. R. Maurer, of the University of Wisconsin, for helpful suggestions and criticisms of the parts of this paper dealing with the laws of mechanics.

For the loan of specimens and slides the writer is indebted to Profs. William H. Hobbs and J. Morgan Clements, of the University of Wisconsin; Dr. Samuel Weidman, of the Wisconsin Geological Survey; Prof. Frank D. Adams, of McGill University, Montreal, and Messrs. Whitman Cross and Ernest Howe, of the United States Geological Survey, Washington; and for a large number of measurements of the dimensions of parallel arranged minerals, to Mr. Sydney H. Ball, of the University of Wisconsin.

PART I.

FLOW CLEAVAGE.

By flow cleavage is meant the cleavage dependent on the parallel arrangement of the mineral constituents of the rock, an arrangement which will be shown to be developed during rock flowage.

In studying flow cleavage the following queries have been kept in mind:

Do the particles of the same mineral species in a cleavable rock show variation in shape, or are they uniform throughout? If they vary, do their dimensions show variations proportional to the amount of deformation which the rock shows? Are the greatest and mean axes of the mineral particles always parallel to the rock cleavage? Do the particles of the same mineral species show a parallelism of their vector or directional properties—i. e., properties related to direction in crystals, such as cohesion, elasticity, optical, thermal, electrical and magnetic properties, and crystalline form? Do the minerals ever exhibit a parallelism of vector properties and not a dimensional parallelism, or vice versa? Are they arranged dimensionally parallel and with no parallelism of their vector properties? Are both dimensional and vector properties parallel; and if so, to what extent? To what extent is cleavage independent of any parallel arrangement of the mineral constituents?

CHAPTER I.

MINERAL ARRANGEMENT IN ROCKS WITH FLOW CLEAVAGE.

Comparatively few minerals make up the great bulk of the rocks possessing secondary flow cleavage. The micas, including muscovite and biotite, chlorite, hornblende, quartz, and feldspar, are in greatest abundance, making up perhaps nine-tenths of them. Other minerals, characteristic though less abundant, are calcite, tremolite, actinolite, garnet, tourmaline, staurolite, chloritoid, sillimanite, etc. Olivine and the pyroxenes are rare in the typical rocks showing flow cleavage, for the most part having been altered to one or more of the minerals above named. In the following discussion the first-named group of minerals will receive the most attention. Discussion of the remaining minerals on the same scale would unduly extend the paper and complicate the conclusions. Many of the features of arrangement of the constituents of cleavable rocks below described are well known, indeed almost axiomatic, to petrographers, but it is necessary again to present them in order to sécure a firm basis for generalizations.

MICA.

Of the minerals in rocks with flow cleavage the micas are by far the most characteristic. Muscovite, sericite, and biotite are the common micas of these rocks, and these alone are considered; statements concerning them will apply nearly as well to the rarer micas. The common association of the micas is with quartz and feldspar, making up rocks which are called, because of the relative abundance of the constituent minerals or because of their texture, micaceous schists, micaceous gneisses, quartzose schists, slates, phyllites, etc. It is preferred in this paper to use the mineral prefix as an adjective, as in the term micaceous schist.

The micas are monoclinic but pseudo-hexagonal in symmetry. The basal plane has a hexagonal or rectangular outline. The characteristic physical feature is the perfect cleavage parallel to the base.

As is well known, mica in cleavable rocks is arranged in plates parallel to its own perfect basal cleavage. The plates are observed to be parallel or nearly parallel to an observed plane of cleavage in the micaceous cleavable rocks. In sections cut normal to the plane of cleavage the mica cleavage plates appear as narrow laths with parallel extinction, usually crowded into layers. Sections cut parallel to the plane of rock cleavage show basal planes of the micas, the biotites nearly isotropic and the muscovites highly refracting. Study of the micas in slides in these two directions yields interesting results.

Mica plates looked at normal to their flat surface do not show any great uniform difference in dimensions. They are commonly of rather irregular shape, sometimes hexagonal and sometimes rectangular, but in any case with slightly unequal dimensions as shown by average measurements. So far as there is any difference in the dimensions of the plates, they may show a small degree of parallelism of their greatest and mean diameters in the plane in which they lie. In some slides a parallelism somewhat similar to that indicated in fig. 1 is to be seen. This in most cases would probably be overlooked if the other minerals in the slide did not usually show a better parallel arrangement of the same kind, and thus indicate where the parallelism of the micas is to be looked for. It will be seen that the mica plates are not strictly parallel to a plane, and hence a section cut parallel to the plane most nearly common to all plates is likely to show oblique sections of many plates, and any faint tendency to parallelism of the greatest and mean diameters of the plates in this plane may not appear in the slide.

FIG. 1.—Rough parallel arrangement sometimes shown by the greatest and mean diameters of mica plates lying in the plane of rock cleavage.

Slides cut across the plane of cleavage of rock containing biotite or muscovite show roughly parallel aggregates of mica plates, bounded by their excellent basal cleavage planes. In cross section they look like laths. The laths are commonly concentrated into layers, with other minerals, such as quartz, intervening (Pl. X). Each mica crystal shows several cleavage laminæ, perhaps due to incipient movement, but the crystal is still evidently a unit.

While there is a characteristic parallelism of mica plates, the deviations from this arrangement are numerous and marked. These irregularities may be seen to be in the neighborhood of harder minerals which have been relatively rigid during deformation, but are present also where the harder minerals are evenly arranged in bands or are very subordinate in quantity. Irregularities are also occasionally due to the development of micas in cracks or along the cleavage of minerals, such as feldspar. The irregularities in the parallel arrangement are of two kinds: (1) They may be due to actual bending or breaking of the mica plates themselves (Pl. II, *B*), in which cases there may be considerable gliding or slipping between the mica laminæ. These bendings are sometimes so great as to make the cleavage more nearly parallel to an axis than to a plane, giving it an approach to linear or "pencil" cleavage (Pl. I). The minute folds so formed may also give a capacity to part parallel to one of the limbs of the fold (Pl. XIV, *B*), thus yielding a structure to which in part the term false cleavage has been applied. (2) Irregularities are formed by unbroken or unbent plates abutting against each other at low angles, producing a characteristic feathering out of one set of laminæ diagonally against another set, as shown in fig. 2 and Pl. II, *A*. A hasty examination of such separate groups of plates gives the impression of bending and breaking, particularly where the micas are about a core of some harder mineral. The angles which these contiguous plates make with one another average less than 15°. Not infrequently this change in direction is accompanied by a change in substance; one mica may be a muscovite and the other a biotite. This curious feathering out of the laminæ of the mica against one another is exceedingly characteristic, and is usually present where there has been no contortion of the mica plates. For its explanation see page 114. It is to be noted that while the irregularities about hard particles give a structure with a mesh appearance, where the micas come together at the ends of a hard particle they do not cross each other, but change their direction in either of the ways above described until they run nearly parallel.

The above description applies to both biotite and muscovite. The two micas, however, show these general features in different degrees, and biotite shows certain features which have not yet been mentioned. It may sometimes be seen in cross section in stumpy porphyritic crystals whose cleavage lies at any angle to the rock cleavage (Pl. III).[a] The other constituents of the rock may bend around them, may stop at their peripheries, or may pass through them without change of direction; in other words, in the last-named case the biotites have the same characteristics of occurrence as have certain of the chloritoids, garnets, etc., described on pages 43–45. Rarely, when the cleavage of porphyritic biotite is uniformly normal to the main rock cleavage, it is found to be parallel to a later developed "false" cleavage (Pl. XIV, *B*). The porphyritic biotites show a characteristic stumpy habit as compared with the biotites developed in plates parallel to the plane of rock cleavage. There may be occasionally observed a breaking down of the porphyritic biotites along their cleavage, the resulting slices having a tendency toward parallelism with one another and with the plane of rock cleavage. Where the process has gone far the porphyritic micas have given way entirely to aggregates of parallel mica plates. The greater diameters of the porphyritic biotites may be parallel or transverse to their cleavage, and thus may form any angle with the rock cleavage.

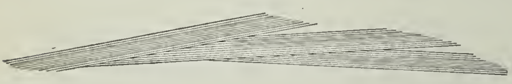

FIG. 2.—Sketch showing the manner in which mica plates feather out, one against the other, in rocks with flow cleavage.

[a] Sp. 1106 H., Williamstown, Mass., slight arrangement; sp. 14930, sl. 7672; sp. 14971, sl. 7709, Black Hills, S. Dak ; sp. 4662 H., southern Connecticut.

Occasionally the biotites occur in flattened lenses with muscovites passing around them, as shown in fig. 3. In this case the cleavage of the biotite is seldom parallel to that of the muscovite and of the rock, but usually makes a considerable angle with the plane of rock cleavage.

Again, the biotite may be associated with quartz, and the two have very much the same relation to the adjacent muscovite. The sketch in fig. 4 shows the biotite and quartz in the same band with muscovite passing around them.

In spite of these differences and irregularities in the biotite and muscovite, commonly the greater diameters of the cleavage plates are parallel, as first described.

As the shapes and dimensions of the micas are commonly those of cleavage pieces of mica crystals, the shapes and dimensions must have uniform relations to other physical properties of the crystals. Hence so far as there is uniformity of arrangement of the dimensional axes of mica plates, there is also uniformity of arrangement of the crystallographic or vector properties. Only one dimensional axis of the mica plates, the shortest, has a tendency toward uniform parallelism in the particles of a cleavable rock. Hence only the physical properties parallel to the shortest diameter of the mica particles are parallel. These are the properties represented by the crystallographic axis *c* and the elastic axis $\mathfrak{a}$.

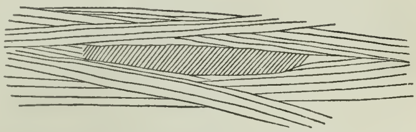

FIG. 3.—Biotite with its own cleavage inclined to rock cleavage, as marked by the adjacent muscovite plates. (Sp. 14901, sl. 7651, Black Hills, South Dakota.)

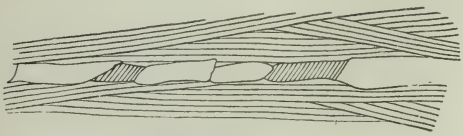

FIG. 4.—Biotite and quartz in a band with parallel muscovite plates adjacent. (Sp. 14901, sl. 7651, Black Hills, South Dakota.)

The elastic axes $\mathfrak{c}$ and $\mathfrak{b}$ in the micas lie in the plane of cleavage. Do these axes in the different mica plates in a secondary cleavable rock lie parallel? In the case of the biotites it was hoped that the determination, by the use of con-convergent polarized light, of the direction of the plane of the optic axis, indicated by the slightly opening cross, would give some information bearing on this subject. However, the optic angle is so small and the basal plane so nearly isotropic that the determinations of the direction of the plane of the optic axes were uncertain and unsatisfactory. A number of such determinations were made in various slides, and such as they were seemed to indicate no parallelism whatever. It is to be noted that the physical differences in the directions of the crystallographic axes in this plane are very slight, and if such characters ever affect the orientation of a mineral they would be little likely to do so here.

In the muscovites, while there are no uniform dimensional differences in the diameters of the plates, the behavior with reference to light, represented by axes $\mathfrak{c}$ and $\mathfrak{b}$, varies somewhat widely. A quartz wedge used with basal sections of muscovite indicates clearly the positions of these axes. About 100 determinations of the position of the optic axes in parallel muscovite plates were made from a dozen selected slides, and no certain parallelism was found in the arrangement of the axes of elasticity. One slide seemed to show a predominance of basal sections with the $\mathfrak{b}$ axis corresponding to the greater dimensional axes of the parallel arranged particles, and the $\mathfrak{c}$ axis in the direction of the mean dimensional axes, but other basal sections in the same slide and in many other slides showed no such arrangement.

Dimensions.—There is little or no difference between the length and breadth of mica plates, as noted in the discussion of basal sections. Between thickness and either length or breadth there is, of course, a marked difference. The ratio of the least to the greatest diameters of the mica plates is generally uniform. Four hundred measurements of both biotite and muscovite from selected slides give an average ratio of greatest to least dimensions of 100 : 16. From this common figure, however, there are many variations. The biotites and muscovites show a uniform difference; the average for biotite is 100 : 20, and that for muscovite is 100 : 14. The various porphyritic and semiporphyritic forms which the biotites sometimes show have an average ratio of greatest to least diameter of 100 : 40, while in the same slides[a] the mica cleavage plates parallel to the plane of rock cleavage, mainly muscovite, have ratios running from 100 : 20 to 100 : 10. In one case[b] the ratio of length or breadth to the thickness of the porphyritic biotites averages 100 : 65, while the muscovites parallel to the plane of rock cleavage average 100 : 13. The measurements of porphyritic biotite above noted are of the greatest and least diameters regardless of the mineral cleavage.

HORNBLENDE.

Common hornblende is a characteristic constituent of a large number of metaclasic rocks. Hornblendic schists are common resultants of the metamorphism under dynamic conditions of intermediate and basic rocks, particularly of igneous origin, such as diorite, basalt, or diabase. They also result from the metamorphism of the sedimentary rocks, such as feldspathic and ferruginous graywackes and slates.

Common hornblende is monoclinic in symmetry, with columnar habit

[a] Sp. 12480, sl. 14846, Wissahickon Creek, Pennsylvania; sp. 14884, sl. 9448; sp. 14901, sl. 7651, Black Hills, South Dakota.

[b] Sp. 14930, sl. 7672, Black Hills, South Dakota.

and prismatic cleavage (fig. 5). Basal sections show the prismatic cleavage in planes intersecting at an angle of 124°.

Examination of the specimens and slides of the hornblendic schists shows the hornblende to occur in characteristic columnar crystal form with linear parallelism or fascicular arrangement (Pl. V). In many cases the crystals are aggregated into indefinite layers. In individual instances there is wide variation from the general parallelism. This variation is likely to be in a plane, and not at angles to this plane—that is, the hornblende crystals, while not parallel to one another, are parallel to a plane.[a] Where the hornblende crystals are best arranged parallel to one another, a section cut parallel to their long dimensions shows the prism faces of the hornblende with only an occasional basal section (Pl. V). Sections cut across the plane of rock cleavage show mainly basal sections with prism faces less conspicuous (Pl. VI). In many cases the longer axes of the cross sections of the hornblende have a tendency (perhaps scarcely noticeable) to lie approximately in the plane of rock cleavage, which thus bisects the acute angles of the hornblende cleavage (fig. 6, and Pl. VI).[b] In slides showing the best arrangement, however, there are numerous wide variations from such parallelism of the axes of the cross sections of the crystals.

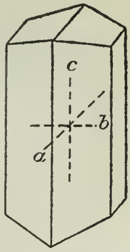

Fig. 5.—Habit of common hornblende crystal.

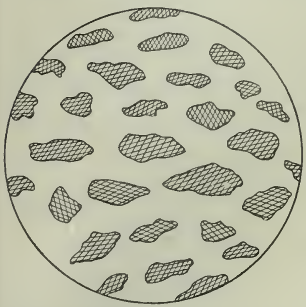
Fig. 6.—Sketch showing tendency toward parallelism of dimensional axes and cleavage of hornblende as viewed in basal section.

In addition to parallel columnar crystals of hornblende, porphyritic hornblende crystals may frequently be observed having considerable variety of shape and arrangement. They are usually short and broad, and their cleavage and greater diameters make almost all angles with the plane of rock cleavage. All stages of the breaking down of such hornblendes may be observed. This breaking down occurs usually, though not always, along the crystallographic cleavage planes and in some cases results in a fairly good parallelism of the slices (fig. 7). In other cases hornblende crystals of different color and evidently of secondary origin are seen to be developing with parallel arrangement out of the porphyritic hornblende.

The hornblende particles in a rock with secondary cleavage being crystals with characteristic habit, and such crystals being arranged

[a] Sp. 1101 H. Croatia.

[b] Sp. 28501, sl. 14854, sp. 28504, sl. 14854, sp. 27750, sl. 13308, Black Hills, South Dakota.

with their greatest, mean, and least diameters respectively parallel, or more commonly with their greatest dimensions parallel, it follows that the vector properties of these diameters must have a proportional degree of parallelism in all crystals. These physical properties, represented by the crystallographic axes, a, b, and c (fig. 8), and the elastic axes, $\mathfrak{a}$, $\mathfrak{b}$, and $\mathfrak{c}$, bear the following relations to the diameters of the particles in the common hornblende. The axis of least elasticity, $\mathfrak{c}$, lies in the acute angle β at an inclination of not more than 20° to the crystallographic axis, c, of the hornblende, and hence to the axis of greatest development. The axis of mean elasticity, $\mathfrak{b}$, corresponds to the crystallographic axis b, or direction of mean development of the crystal. The axis of greatest elasticity, $\mathfrak{a}$, lies in the obtuse angle B at an inclination of not more than 30° to the crystallographic axis, a, the direction of least dimensional development. Where all the dimensional axes are parallel, the vector properties represented by these axes are also parallel. Where the mean and least diameters of the hornblende have no uniform parallelism, the only vector properties that are parallel to one another are those parallel to the greatest dimension—the crystallographic axis c and the axis of elasticity $\mathfrak{c}$—while the properties represented by a or b are parallel to a plane and not to each other. Where all the hornblende crystals are not parallel to one another, but are parallel to a plane, the shortest diameters of the particles may be uniformly at right angles to this plane, and hence the axes a and $\mathfrak{a}$ in different crystals may be also parallel. However, observation shows that when the greatest dimensions of the hornblende crystals are not parallel to one another, but only to a plane, the mean and least diameters are not likely to be parallel to one another.

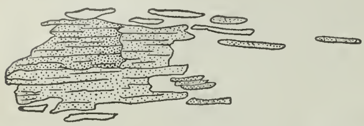

FIG. 7.—Slicing of hornblende. (Sp. 40685, sl. 15360, sp. 40690, sl. 15363, hornblende schist, Mesabi district of Minnesota.)

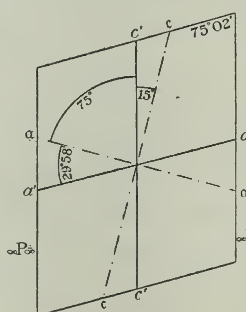

FIG. 8.—Cross section of hornblende crystal parallel to clinopinacoid (parallel to axes a and c in fig. 5), showing positions of crystallographic and elastic axes.

Dimensions.—One hundred and fifty measurements were taken of the dimensions of the hornblende crystals in prismatic section from 15 selected slides. A striking uniformity was found in the ratio of the length of the longest diameters—i. e., the dimensional axes corresponding to the columnar development—to the length of the shorter ones at right angles to them. This ratio varies between 100 : 25 and 100 : 20. The ratio between the mean and the least diameters of the crystals, as seen in basal sections, averages about 100:60, and corresponds well with the ratio calculated for the crystal form.

There appears to be a difference between the dimensions of hornblende crystals in secondary-cleavage rocks and the dimensions of hornblende crystals in original igneous rocks which have not been deformed since their solidification. Measurements (125) of original hornblende crystals in a number of selected hornblendic granites and diorites and more basic hornblendic rocks showed that the ratio of length to breadth or thickness ranged from 100:30 to 100:75, with 100:40 common.

QUARTZ.

Quartz is a common and abundant constituent of the more acidic cleavable rocks. Its common associates are mica and feldspar in rocks which are named quartzose schists, micaceous schists, micaceous gneisses, slates, phyllites, etc., according to the relative abundance or the cleavage-making importance of the minerals composing them.

The quartz crystal is hexagonal, commonly of short, columnar, habit, and lacks good cleavage. The quartz observed in rocks with secondary cleavage is described below according to its characteristic shape. Later it will be shown that the shape is dependent on the manner of development.

(1) Quartz occurs in particles that have more or less modified crystal outlines and grade into irregular, rounded to subangular forms; the crystal outlines are rare, while the irregular, rounded to subangular forms which grade into the forms described under (3) are common. The crystal forms when present rarely show any tendency toward parallelism, dimensional or crystallographic. The irregular forms sometimes have a dimensional arrangement and sometimes not. In no case do they have a uniform crystallographic arrangement. The ratio of the greatest to the least diameters of this group varies from 100:100 to 100:50 or less. A common ratio is not far from 100:75.

(2) Quartz occurs in angular fragments, which apparently owe their shape mainly to the fracturing of larger particles, and in forms that grade from angular fragments to the grains described under (1). Gradations in the fracturing of the larger particles are to be observed, beginning with undulatory extinction and ending with granulation of every original particle. The fine lines of undulatory extinction perhaps associated with lines of inclusions that represent the intersection of a plane with the slide not infrequently occur in sets crossing each other at angles approaching 90° and making an angle of 45° to the plane of rock cleavage. Not infrequently, in intermediate stages, the residual material left in grains which have been subjected to granulation may be seen to have roughly lenticular shapes (augen), the long direction being parallel to the plane of rock cleavage. This lenticular appearance is emphasized by the occurrence of granulated quartz in tails at the ends of the nongranulated

material. Parallel quartz particles developed by the parallel fracturing or slicing of a large quartz individual are also not uncommon. The fractures may be mainly in one set of planes and are either parallel to or inclined at a low angle to the plane of rock cleavage as conditioned by the other constituents of the rock (fig. 9). Close to the point where the slicing occurred the length of such slices may be from two to six times their breadth, but a short distance away particles of apparently the same shape have been broken into small pieces. In advanced stages of granulation the quartz particles have been strewn out and left in nearly even layers.

As soon as any of the micaceous minerals begin to be in evidence the quartz is likely to show undulatory extinction. The advanced stage of the granulation of the quartz is usually reached before the feldspar begins to show signs of pressure. Early stages of granulation of the quartz, with the mica well developed and the feldspar still

FIG. 9.—Slicing of quartz grain in schistose conglomerate (Metropolitan, Mich., large slide No. 1).

unaffected, are well exhibited in some of the Black Hills schists. A schist[a] from the Medicine Bow Mountains, Wyoming, shows well-advanced granulation of the quartz, while the feldspars show only peripheral granulation.

The granulated quartz particles are usually unequidimensional and in 100 fractured particles the ratio of the greatest to the least dimensions ranged from 100:50 to 100:100, with an average of 100:75. The most angular pieces are in many cases the small ones, although it can hardly be said that, on the average, the smaller the particles the more angular they are. The longer diameters of the particles[b] in the earlier stages of the granulation are commonly in random positions. In later stages they show a very slight tendency to parallelism to the observed cleavage in the rock, as above noted. This is due to rotation, as will be seen below.[c]

The dimensional arrangement of the quartz particles, formed by fracturing in advanced stages of the granulation, carries with it, as shown by the varying extinction, no crystallographic or vector arrangement whatever. In early stages of fracturing the angular

[a] Sp. 15570, Medicine Bow Mountains, Wyoming.
[b] Sp. 14815, sl. 7577, sp. 14817, sl. 14849, Black Hills, South Dakota; sp. 923 U. W., Dittersdorf, Saxony.
[c] Sp. 15665, sl. 8084, Medicine Bow Mountains, Wyoming.

pieces derived from the breaking down of a single large particle may have similar crystallographic arrangement, but the particles derived from different crystals show no such parallelism.

(3) Quartz appears in a variety of elongated lens-shaped, ribbon-shaped, and spindle-shaped forms, with their longer axes parallel or inclined to the plane of cleavage. Lenticular or augen forms composed of single individuals developed by peripheral granulation have already been described in connection with the granulated forms discussed under (2), p. 31. Other flattened lenses, with outlines curved and even, made up usually of several individuals, give no evidence of development by granulation and slicing. They lie with their longer axes in the plane of rock cleavage, and are usually a little more elongated in one direction than in another. In some cases this elongation is very marked and the cross section is a flattened lens.[a] Whether or not the lenses show a difference of dimensions in the plane of rock cleavage, they commonly have considerable length or breadth as compared with their thickness (Pls. VII, VIII, IX, X). It is not uncommon to see a lens extending the length of a hand specimen, and to have a thickness of only 0.25 mm. Each lens may be made up of a number of crystal individuals lying side by side. The individuals themselves usually, though not always, have their greater dimensions in the plane of rock cleavage, the ratio of the greatest dimension in the plane of rock cleavage to the thickness of the crystal averaging perhaps 100:50, but varying from 100:20 to 100:100. These figures were determined by 200 measurements from 20 selected slides.

FIG. 10.—Sketch showing granulation of quartz (A) where feldspar (B) is comparatively unaffected by deformation.

The lenses above described, consisting of several individuals lying side by side, grade into shorter lens-shaped forms, consisting mainly of a single individual, although the "tails" may be formed of smaller separate particles. These forms are really phenocrysts (Pl. XI, *A*). These single crystals in flattened lenses in turn grade into spindle-shaped forms which are elongated in one direction and shortened in all directions normal to this. The ratio of the length to the thickness of the individual crystals varies widely. In the quartz-porphyry from the Thüringer Wald described by Futterer,[b] it varies from 10:1 to 2:1.

[a] Sp. 18845, sl. 10185, Laurentide Mountains, Canada.

[b] Futterer, Karl, Ganggranite von Grosssachsen und die Quartzporphyre von Thal im Thüringer Wald: A thesis presented to the University of Heidelberg for the degree of Ph. D., 1890, p. 48. Sp. 88.

The arrangement of the quartzes in parallel lenses and spindles may be observed in slides in which the feldspars have not been at all deformed. In the quartz-porphyry from the Thüringer Wald (Pl. XI), all stages of deformation of the quartzes into these forms may be observed, while the feldspars in many cases at least are relatively undeformed or deformed only by fracture.

In the forms described under (3) dimensional arrangement usually does not carry with it a crystallographic arrangement of the individuals. The crystallographic arrangement is entirely random, as shown by the extinction of different particles at different times when revolved under crossed nicols. In the slides which have been examined during this investigation the quartz-porphyry from the Thüringer Wald shows a parallelism of the crystallographic *c* axes to each other, to the greatest development of the crystals, and to the plane of rock cleavage. This may be an original orientation retained during deformation.

In the above lens- and spindle-shaped forms, both in layers and in separate individuals, one feature of the crystallographic arrangement is of special interest. Not infrequently, where the particles lie in such a position that their *c* axes are in the plane of rock cleavage, and particularly where the crystals show strain effects, such as undulatory extinction, sections cut normal to the *c* axis show the quartz not to be optically uniaxial, but to be slightly biaxial, and the plane of the optic axes to lie normal to the plane of rock cleavage. This position of the plane of the optic axes is what would be expected from the flattening of a uniaxial ellipsoid of elasticity in the plane of rock cleavage. Futterer[a] describes this feature in the Ganggranite von Grosssachsen, and in the quartz-porphyry of the Thüringer Wald. Other similar crystals lying with their *c* axes in the plane of rock cleavage are optically uniaxial, but in such cases strain effects are usually lacking. The biaxial nature of the quartz appears itself to be a strain phenomenon.

The relative abundance of the forms of quartz particles above described of course varies widely in different cleavable rocks. Probably, however, in the quartzose cleavable rocks as a group the forms described under (1) and (2) occur in greatest abundance. The flattened lens-shaped forms described under (3) are less abundant, but are very characteristic of cleavable rocks which have undergone severe metamorphism. The spindle forms described under (3) are of rare occurrence.

It appears from the above account that the occurrence of quartz in

[a] Ibid., pp. 20, 34.

cleavable rocks is essentially different from that of mica or hornblende. Mica and hornblende are usually in crystals with characteristic habit, with good dimensional arrangement, and for the most part with a good crystallographic arrangement. Quartz, on the contrary, is characteristically without crystal habit; the shape of the particles varies somewhat with the nature and amount of the deformation which the rock has undergone, and, except in rare instances, there is no crystallographic parallelism.

FELDSPAR.

Feldspar is present in considerable quantity in the gneisses, micaceous schists, hornblendic schists, chloritic schists and slates, and, in fact, in all of the metaclasic rocks, with the exception of certain ultrabasic and quartzose schists.

In the following discussion the various feldspars are not discriminated except in descriptions of individual specimens. The differences in arrangement between the varieties are numerous, but for the purposes of this paper a general statement covering the feldspars as a group is sufficient.

The feldspars occur (1) in forms that have more or less modified crystal outlines, (2) in small, nearly equidimensional particles, with irregular angular outlines, and (3) in ellipsoidal or lenticular forms with curved or angular outlines. Between these all intermediate shapes are to be observed. In each of these classes the feldspars show minor differences of occurrence, the description of which would involve the discussion of the processes by which they are arranged. These differences will be ignored here as far as possible and will be described in connection with the processes of arrangement on pages 87–89.

(1) The feldspars that have more or less modified crystal outlines may have their longer diameters arranged (*a*) at random or (*b*) parallel to the plane of rock cleavage.

(*a*) The crystals with random arrangements in many cases crowd the other parallel constituents of the rock, which bend around them. In other cases the parallel constituents are not crowded, but about against the feldspars without any bending and even pass through them without change of direction.[a]

(*b*) Where the crystals lie with their greater diameters parallel to the plane of rock cleavage, there is a tendency toward uniformity of arrangement of the crystallographic axes and of the feldspar cleavage which requires special description. Several good cases of this arrangement have been observed and two of these will be described in detail.

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[a] Sps. H. 1060, 1068, Greylock, Mass.

The first is that of the Hoosac schist[a] of Massachusetts, representing an extreme case of metamorphism. It is a micaceous quartzose schist with large albite phenocrysts. The mica and quartz are arranged in bands. The porphyritic albites include parallel particles of quartz and biotite (Pl. XIII, *A*). The micas abut against the albites frequently without the slightest change of direction; they are not crowded, and do not bend around the albites. The feldspars themselves lack evidence of mechanical deformation. Their greater dimensions lie in the plane of rock cleavage. The ratio of the greatest to the least dimensional axes of the feldspar particles, determined by 100 measurements from 10 selected slides, varies from 100 : 50 to 100 : 75.

An examination of these feldspars in sections cut across the plane of rock cleavage shows that the elongated feldspars have a marked tendency toward parallel extinction. The angle of extinction with the long side of the crystal and with the rock cleavage varies from 0 to 19°. Many crystals also show simple twins; the twinning plane cuts across the short direction of the crystal, and frequently lies normal to the plane of rock cleavage (Pl. XIII, *A*). Other crystals show a twinning plane parallel to the longer dimensions of the crystal—that is, parallel to the rock cleavage. Albite with a simple twinning has two habits, a common tabular development parallel to the brachypinacoid, and a less common tabular development parallel to the macropinacoid (figs. 11, 12). The relation of the twinning lines tc the shape of the feldspar sections in this rock shows that crystals of both habits evidently are present. The greatest diameters of the feldspar particles lie in the plane of rock cleavage but are not parallel.

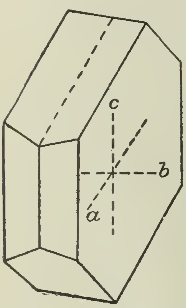

FIG. 11.—Twinned albite crystal with brachypinacoidal development.

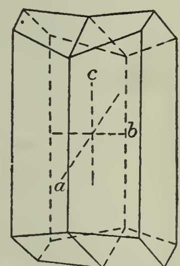

FIG. 12.—Twinned albite crystal with macropinacoidal development.

Another case of parallel arrangement of feldspar crystals is in a mashed feldspar rock from the Wausau district of Wisconsin, described by Weidman.[b] This rock has been subjected to severe metamorphism, acquiring thereby a parallel arrangement of its mineral constituents.[c] The feldspars are in separate parallel tabular crystals, and also in the parallel flattened lenses described in a subsequent paragraph. Where they are in crystals (albite), the tabular brachypinacoidal faces are parallel to each other and to the rock cleavage. The longest diameters are parallel to the plane of rock cleavage, but not necessarily to each other.

[a] Sp. 18062, sls. 14972, 14973, 14974, Hoosac tunnel, North Adams, Mass.

[b] Bull. Wisconsin Geol. Nat. Hist. Survey, in preparation.

[c] A considerable portion of the rock shows an original parallel arrangement of different origin, which will not be here discussed, but which is not confused with the particular phenomenon described.

This is the arrangement shown by part of the albite crystals of the Hoosac schist. The average ratio of the greatest to the least diameter is 100 : 20.

In albite the axis of elasticity, $\mathfrak{c}$, is approximately normal to the brachypinacoid, while the axis of elasticity, $\mathfrak{a}$, is nearly normal to the macropinacoid. In the parallel arranged albites above described, therefore, these axes have different positions, depending upon which of the two tabular developments is present and controls the arrangement. Where the tabular development is parallel to the brachypinacoid, the common case, the axis $\mathfrak{c}$ is normal to the cleavage of the rock. The axes $\mathfrak{a}$ and $\mathfrak{b}$ are not parallel, but lie in the same plane. Where the tabular development is macropinacoidal and the feldspar is arranged parallel to this plane, the axis of greatest elasticity $\mathfrak{a}$ always stands normal to the plane of rock cleavage determined by the dimensions of the crystals. The axes $\mathfrak{c}$ and $\mathfrak{b}$ in this case are not parallel to each other, but are parallel to the plane of rock cleavage.

Fig. 13.—Microscopic view of fresh anorthosite. (Cf. Adams, Geol. Survey, Canada: vol. 7, 1894, pt. J.

(2) The angular particles clearly owe their shape principally to the granulation of larger particles, although they may be partly original and partly due to other causes. The first effects noticeable in the mechanical deformation of a feldspar crystal are twinning lamellæ and peripheral granulation. With increasing deformation there is gradation from these phenomena to complete granulation of the particles. At an intermediate stage of deformation the feldspar crystal may have a lenticular form. Where the small particles ground off from a large particle lie close at hand, forming a "tail," the group forms a conspicuous lenticule, or "augen." At later stages of granulation the minute particles not infrequently lie in a layer of uniform thickness.

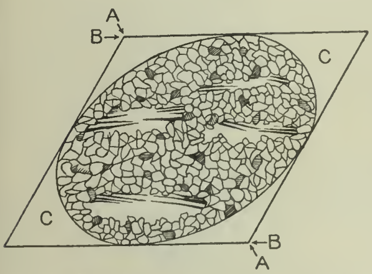

Fig. 14.—Microscopic view of anorthosite after granulation. The residual feldspars may lie with their longer axes parallel or inclined to the elongation of the rock as a whole.

In the sheared anorthosite from north of Montreal, described by Adams,[a] feldspar particles in parallel, elongated, sometimes ribbon-like forms, with irregular angular borders may be seen lying in a matrix of finely granulated material (figs. 13 and 14; also Pl. XII, *B*). Measurements show that the larger feldspars have been granulated into nearly 70,000 small particles. The residual feldspars show strain

[a] Adams, F. D., Report on the geology of a portion of the Laurentian area lying north of the island of Montreal: Geol. Survey of Canada, vol. 8, pt. 1, 1896, Pl. VII.

shadows grading into minute fractures. Granulation of feldspars is well exhibited in the Berlin rhyolite-gneiss of Wisconsin (Pl. XII, *A*).

Occasionally the fracturing of feldspar particles has resulted in their division into parallel slices, either parallel or inclined to the plane of rock cleavage as conditioned by the other constituents of the rock mass (figs. 15, 16, 17; Pl. XI, *B*). Usually the fractures producing such slices are in one set of planes at a low angle with the plane of elongation of the rock mass as a whole, but sometimes also in intersecting planes.

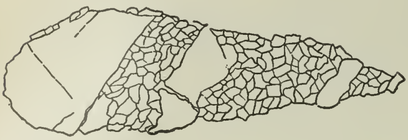

FIG. 15.—"Sliced" feldspar in rhyolite-gneiss. (Berlin, sp. 3813, Wis. Survey.)

In the early stages of mechanical deformation there is practically no parallel arrangement of the greater diameters of the minute granules developed by granulation. In subsequent stages the angular particles, through rotation, have a very slight tendency to lie with their longer diameters parallel to the plane of rock cleavage. In many thin sections of rocks with fair secondary cleavage, the mica and hornblende, and even the quartz, have their longer diameters parallel, while the angular feldspar particles show no tendency to such arrangement. Where best developed the dimensional parallelism is hardly noticeable on a cursory examination. A reason for this appears in the fact that the angular particles as observed in the cleavable rocks have such slight differences in dimension. The ratio of the greatest dimensional diameters to the least, obtained from 100 measurements from 10 selected slides, is in extreme cases 100:40, while the average is more nearly 100:60.

FIG. 16.—Feldspar showing incipient "slicing" in schist-conglomerate. (Metropolitan, Mich., large slide, No. 1.)

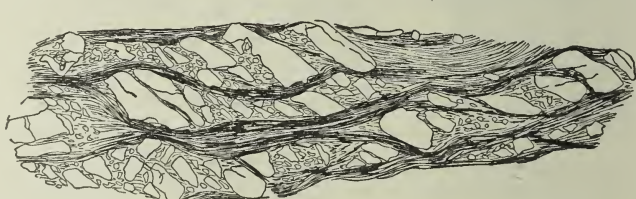

FIG. 17.—"Sliced" feldspars in micaceous and chloritic schist from southern Appalachians.

The slight dimensional arrangement of the minute feldspar granules carries with it no tendency toward a parallel crystallographic arrangement, so far as the observations made in this study have gone, except in the infrequent cases of the slightly moved slices of individual feldspar particles. Diligent search has failed to reveal even a faint tendency toward parallelism; if present at all it must be in exceptional cases. This comes from the fact that the relations of the dimensions of the granulated feldspar particles to the crystallographic properties are ordinarily not uniform, and even where they are partially uniform, the tendency toward dimensional arrangement due to difference in dimensions is so slight that uniformity in crystallographic arrangement is not evident.

It is to be noted that most of the fragments formed from a single sliced individual have close approach to crystallographic parallelism, although there is no parallelism between the pieces formed from the slicing of different feldspar particles; also that there has frequently been rotation of these slices toward a common plane inclined to the planes of fracture and parallel to the longer diameters of other constituents which have developed in a parallel position by another process shown later to be recrystallization.[a]

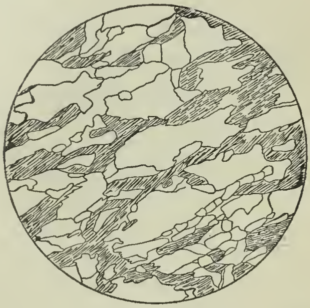

FIG. 18.—Feldspar in parallel lenses with crystallographic parallelism. The longer axes of the lenses are approximately in the brachypinacoid. From hornblendic schist of Mesabi district of Minnesota.

(3) The remaining occurrences of feldspar to be described have lenticular or ribbon forms with their flat surface in the plane of rock cleavage. These forms show all gradations into both the angular feldspar particles and the feldspar crystals above described. In the nepheline-syenite of the Wausau district and in a hornblendic schist from the Mesabi district of Minnesota[b] the lenses of albite either occur as separate individuals or lie end to end and form lens-shaped layers of considerable extent (fig. 18). Many of the feldspars in the lenses or layers show no uniform relations of their dimensions to the crystallographic properties.[c] The feldspars extinguish at various angles, like the quartz lenses of similar shape described in the preceding section. The ratio of the greatest to the least axes of the individuals is 100:30. In other cases the greater dimensions of the albites of the lenses or layers correspond roughly with the tabular developments parallel to the brachypinacoid, in which case there is a tendency to extinguish parallel to the longer diameters of the lenses, although the extinction varies from 0 to 20° or 30°.[d] There is a characteristic lack of strain effects, although the rock gives evidence of deformation. The axis of elasticity $\mathfrak{c}$ is parallel to the shorter diameters of the lenses and thus transverse to the cleavage of the rock.

In general the feldspar particles in rocks with secondary flow cleav-

[a] Cf. Lehmann, Atlas, Pl. XXI, fig. 3.

[b] Sp. 45492, sl. 15759, Mesabi district of Minnesota.

[c] Sp. 6022A, Wausau, Wis. Cf. Weidman.

[d] Sp. 6024C, Wausau, Wis. Cf. Weidman.

age are present in quantity in the order in which they are described above. The common parallel arrangement of feldspars is thus dimensional, although, even where the dimensional arrangement is best, the approach to parallelism of the longer diameters of the particles is not close. Rarely the parallel arrangement is also crystallographic, in which case the good basal cleavage of the feldspar is normal to the plane of the greatest and mean dimensional axes, and hence to the plane of rock cleavage with which the longer axes are parallel. The poorer brachypinacoidal cleavage or clinopinacoidal cleavage is in most cases parallel to the plane of tabular development and the rock cleavage, but in a few cases is normal to it.

CHLORITE.

Chlorite is characteristic of chloritic schists or slates. The development of such cleavable rocks may be in part under conditions somewhat different from those under which metaclasic rocks containing mica or hornblende are developed.[a]

Not infrequently chloritic schists result from the alteration of biotitic schists, and in such cases the chlorite is essentially pseudomorphic.

Chlorite is monoclinic, but pseudo-hexagonal, with prismatic habit, and with excellent basal cleavage.

In cleavable rocks the mineral occurs in cleavage plates that have their flat surfaces parallel to the rock cleavage in a manner similar to that of the micas. It appears also in irregular and ill-defined aggregates. Because of its tendency to hexagonal development, the greater diameters of the cleavage plates are not markedly unequal in length, and thus no parallelism of greatest and mean diameters in the plane of rock cleavage can be looked for. The ratio of the thickness of the plates to the diameter is about the same as in the micas, in average cases perhaps 16:100. As in biotite, the axis of greatest elasticity $\mathfrak{a}$ is normal to the cleavage plane. The axes $\mathfrak{b}$ and $\mathfrak{c}$ lie in the plane of rock cleavage, but are not parallel in different cleavage plates. Chlorite has the same manner of aggregation into layers etc., as the micas.

CALCITE.

Cleavable marbles are not abundant, notwithstanding the great number of limestone formations which have been subjected to extreme metamorphism. Neither is calcite an abundant secondary constituent in cleavable rocks in which other constituents, such as mica and hornblende, are predominant. The conditions favorable for the development of such constituents apparently do not favor the development of secondary calcite. Indeed, under such conditions there is a marked tendency toward the replacement of calcite by silicates. The

[a] See discussion of development of chlorite in Van Hise's Treatise on Metamorphism: Mon. U. S. Geol. Survey, vol. 47, 1904.

arrangement of the calcite in cleavable marbles is of principal interest, and to this the description below is mainly restricted.

Calcite has hexagonal rhombohedral form, with, in general, a tendency to columnar development parallel to *c* when crystal outlines are present. Its cleavage parallel to the rhombic faces is excellent, and polysynthetic twinning parallel to $-\frac{1}{2}R$ is a common feature.

Calcite in marbles with flow cleavage appears in two ways—(1) in small nearly oval grains, and (2) in small angular pieces. Another occurrence is discussed under fracture cleavage on pp. 119–121.

(1) Some of the most cleavable marbles examined, especially those from Talledega Mountain, Georgia,[a] were seen to have a distinctly granular aspect and to be made up of oval grains of calcite of somewhat uniform size, arranged with their dimensional diameters in a common direction parallel to the observed rock cleavage (fig. 19). Between these grains may be a considerable amount of finely granulated material. Few strain effects, such as fractures or close polysynthetic twinning, are to be observed. The dimensional parallelism is well marked. No crystallographic parallelism accompanies the dimensional parallelism. The grains extinguish at different angles, and their cleavage lies at all angles with the greatest dimensions of the particles.

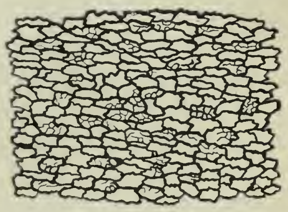

FIG. 19.—Parallel grains of calcite in schistose marble. (Special slides I, III, Talledega Mountain, Georgia.)

In the cleavable marbles the ratio of length of these parallel grains to breadth, as determined by 100 measurements from 10 selected slides, is from 100:32 to 100:60. This ratio is not far different from that obtained in marbles showing no cleavage, in which a number of measurements give an average of 100:73.

(2) The calcite particles may sometimes be seen in irregular angular pieces. Commonly their greatest and least diameters are not far different from those described under (1), and gradational phases into (1) are noted. There is a slight tendency to parallel arrangement, which is dimensional and not crystallographic. In those rocks examined the angular particles are not so common as the ellipsoidal grains described under (1).

While the accessory calcite occasionally found in micaceous schists, quartzose schists, or hornblendic schists, is perhaps partly original, it is in many cases a secondary replacement of other minerals after the cleavage of the rock has been produced. It may fill irregular elongated areas left by the solution of other minerals, although, in general, in rocks of this sort there is little tendency for parallel dimensional arrangement of the calcite. In no case is crystallographic arrangement observed.

[a] Sp. 18083, sl. 9626, Green Mountain Range, Vermont; sp. 18192; sls. I, II, III, IV, Talledega Mountain, Georgia; near Comstock, N. Y.; Cambro-Silurian marbles of western Massachusetts described in Mon. U. S. Geol. Survey, vol. 23, 1894, Laurentian marbles.

TREMOLITE, ACTINOLITE, GRÜNERITE, AND OTHER AMPHIBOLES.

These minerals are especially characteristic of cleavable rocks formed by the metamorphism of calcareous and sideritic rocks and known as tremolitic schists, actinolitic schists, and grüneritic schists. They are characteristically developed by contact metamorphism, but are formed also at considerable depths under conditions of high temperature and pressure. They are all monoclinic, with a marked prismatic or acicular development. They occur either in single crystals, or, characteristically, in sheaf-like or radial aggregates.

In cleavable rocks the undoubted characteristic occurrence of these minerals is in radial and fascicular aggregates with entirely random arrangements. Occasionally the individual crystals are arranged with their longer dimensions in the plane of rock cleavage, though rarely parallel to each other in this plane. The arrangement is not conspicuous and might be overlooked, but on examination in a slide the crystals, especially those of actinolite or grünerite, are seen to cross each other at acute angles, perhaps 40°, and lines bisecting these angles are seen to have a common direction. The best cases of parallelism are observed where the crystals are in single individuals. Where the crystals are in the sheaf-like and radial aggregates, the rays lying in the plane of rock cleavage are likely to have a greater development than those crossing it. Between random arrangement and this tendency to parallelism there is complete gradation; but the former is believed to be by far the more common. Where the parallel arrangement is best developed, no data are at hand to determine whether or not the amphiboles of this group have their shorter axes parallel, like hornblende. From analogy to the hornblende it is reasonable to suppose that this is sometimes the case. So far as this may occur, the crystallographic and elastic axes would have the same relations to the plane of rock cleavage as in common hornblende.

KAOLIN AND TALC.

Talc is largely the result of weathering, but in places it forms cleavable rocks. It is similar to mica and chlorite in habit and arrangement.

GARNET.

Garnet is probably the most common of the porphyritic minerals of the "crystalline schists." In extremely metamorphosed cleavable rocks, and especially in the micaceous schists and in phyllites, porphyritic garnets may be seen.

The garnets are isometric, and thus show no dimensional or crystallographic variations along their different axes. In the rocks examined their diameter is commonly not less than 1 mm., and is occasionally 4 cm. Being equidimensional, the individual crystals can be said to have no dimensional arrangement with reference to the plane of rock cleavage. However, an examination of secondary cleavable rocks shows that, in many cases at least, the garnets are more numerous in certain planes of cleavage than in others. They are likely to occur along planes where mica has been abundantly developed, and are not so numerous in the quartz and feldspar layers.

TOURMALINE.

Tourmaline is characteristic of the micaceous schists and certain feldspathic schists. Its development is commonly supposed to be largely due to the contact action of the magma and the introduction of extraneous material into the metamorphosed rock.

The mineral is hexagonal (trigonal), with a marked columnar habit. In the rocks with secondary cleavage the columnar crystals of tourmaline have a marked tendency to lie parallel to the plane of rock cleavage, but not to one another.[a] In a few cases they are parallel to one another as well as to the plane of rock cleavage.[b] There is no parallelism of the shorter axes, except to a plane, when the longer axes are parallel.

So far as the crystals have dimensional arrangement the crystallographic properties also are parallel. The crystallographic axes, *c*, or the principal optic axes (negative) in the different particles thus lie in the plane of cleavage and rarely are also parallel to one another in this plane. The crystals vary considerably in the ratio of their greatest to their smallest diameters; 100 : 60 and 100 : 20 are extremes from 25 measurements in 5 selected slides and specimens.

STAUROLITE.

Staurolite is characteristic of micaceous schists. It is orthorhombic, and characteristically in short tabular crystals and cross twins, in each case with a well-marked development parallel to the macropinacoid. The arrangement of the staurolite in the secondary cleavable rocks may be observed macroscopically, and especially well on a weathered surface. An examination of numerous specimens shows that the staurolites have a strong tendency to lie with their flat surface parallel to the plane of cleavage,[c] although many exceptions to this rule are noted. The greater axes of the crystals in this plane are not parallel.

As the staurolites in crystal form have uniform relations of their

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[a] Sp. H. 1049.1, Hoosac Mountain, Massachusetts; sp. H. 4154B, near Seymour, Conn.; sp. H. 4151, Beacon Falls, Conn.; sp. H. 4083, A, near Danbury, Conn.

[b] Sp. 14889, Black Hills, South Dakota; sp. 29633, Laramie, Wyo.

[c] Sp. H. 1105, west side Conanicut Island, Narragansett Bay; sp. H. 1084, Conn., sp. 14919, Black Hills, South Dakota.

crystallographic axes to the dimensional axes, it follows that the crystallographic properties of the crystals are arranged to the same degree as the dimensional axes. The crystallographic axis *c* and the axis of greatest elasticity $\mathfrak{a}$ thus lie in the plane of cleavage.

OTTRELITE (AND CHLORITOID).

Ottrelite and chloritoid are found principally in the micaceous schists or phyllites. They are closely related in their properties and occurrence, and are commonly not discriminated, although they seem to differ in chemical composition. The minerals are monoclinic and the basal cleavage is good, although it is not so perfect as in mica.

They occur in the micaceous schists or phyllites in a variety of ways—in radial or sheaf-like aggregates, in thin scales or plates, and in simple crystals. In the rocks examined the ottrelite has predominantly crystal form. The crystals are more or less hexagonal, tabular plates, with a good basal cleavage parallel to their longer dimensions. "Hourglass" twins are not uncommon.

In the typical ottrelite-schist from Ottrez, Belgium,[a] the ottrelites have no parallel arrangement whatever, dimensional or crystallographic. In rocks from other localities, however, there is a tendency for the dimensions of the plates to control the arrangement of the crystals, causing the greater dimensions to lie more nearly in the plane of cleavage than normal to it. Within this plane the greater dimensions of the crystals make all angles with one another. The mica-schists of the Black Hills, South Dakota,[b] show this arrangement. The tendency toward parallelism is slight, even where most marked, and in rocks showing such arrangement many ottrelite crystals lie squarely across the rock cleavage and at all angles to it. The result is that any rock with secondary cleavage containing ottrelite is likely to show ottrelite cleavage faces on any surface, but more conspicuously in the zone normal to the plane of rock cleavage, for in the plane of rock cleavage the mica cleavage (the ottrelite is commonly associated with mica) is likely to obscure the cleavage of the ottrelites.

The average ratio of the length of the crystals to the breadth, taken from 100 measurements from 10 selected slides, is 100:40.

ANDALUSITE (CHIASTOLITE).

Chiastolite is not important as a cleavage-giving mineral, but it is characteristic of certain dense cleavable hornfels in which long, prismatic, chiastolite crystals stand out conspicuously against a fine-grained, dark-colored background. The mineral is orthorhombic with columnar habit. In most of the rocks with secondary cleavage that were examined the chiastolite crystals were either inclined or perpen-

[a] Sp. H. 1104, Ottrez, Belgium. [b] Sp. 14874, Black Hills, South Dakota.

dicular to the plane of rock cleavage,[a] but in certain of the rocks there is a tendency for the long directions of the crystals to lie roughly in the plane of rock cleavage.[b] The greatest and mean axes have no parallelism in this plane. The average ratio of length to breadth, measured in 30 crystals from 3 slides, is 100:10.

As chiastolite occurs in crystals whose dimensional and crystallographic properties are uniformly related, it follows that the crystallographic properties are parallel so far as the dimensional axes are parallel. The properties represented by the *c* axis are thus parallel to a plane and not to a line.

SILLIMANITE (FIBROLITE).

This is a rare constituent of the cleavable rocks as a whole, and even where most abundant makes up but a small portion of the rock. It is orthorhombic, with a very strong columnar habit.

In the cleavable rocks sillimanite is seen to occur in single, slender, rod-like forms, with characteristic cross fractures, and also in sheaf-like aggregates and parallel bunches. The individuals and the crystals in aggregates have a strong tendency toward a parallelism of their longer axes.[c] They furthermore have a tendency toward concentration into definite layers.[d] The individuals are always slender, frequently almost hair-like, and their length as compared with their thickness is very great. On account of the fineness and cross fracture average measurements are not practicable. The crystallographic axis *c* and the axis of least elasticity, $\mathfrak{c}$, lie in the plane of rock cleavage.

SUMMARY STATEMENT CONCERNING FACTS OF ARRANGEMENT IN ROCKS WITH FLOW CLEAVAGE.

The above facts are believed to afford a basis for the following generalizations:

Rocks with flow cleavage are made up principally of flat or elongated particles with a variety of shapes and dimensions. Particles of a particular mineral have characteristic shapes and dimensions and are easily distinguished from particles of other minerals. Occasionally, however, they show minor variations of form due to differences in origin and behavior during deformation. To illustrate: Mica is in thin plates; hornblende is columnar; quartz is seldom in crystal form, but is in angular or lenticular grains; feldspar is sometimes in crystal or lenticular form, but usually in angular to subangular grains. The ratio of the greatest to the least diameter varies in mica from 100:20 to 100:10; in hornblende, from 100:20 to 100:25; in quartz from

[a] Sp. H. 71.1, Yaqui Gulch, California.

[b] Sp. H. 1112.1, H. 71, Gefrees, Fichtelgebirge, Germany.

[c] Sp. 14 Bayley, sp. 504 Bayley, sp. 906 W., Saxony, sp. 14901, sl. 7651 Black Hills, South Dakota.

[d] Sp. 504 Bayley.

100:50 in common cases to 100:15 in exceptional cases; in feldspar it is about 100:60. The uniformity of this ratio for a given mineral species disproves the idea sometimes held that the degree of flatness or elongation of particles in a rock with secondary cleavage is proportional to the amount of deformation which the rock has undergone.

The unequiaxial particles of the rocks with flow cleavage have a tendency to lie with their greater, mean, and least diameters parallel to one another, although this tendency varies with the nature of the mineral, with the processes which have been effective in bringing about the arrangement (as will be shown in a subsequent chapter), and with the amount of deformation which the rock has undergone. There is also a tendency for minerals of the same kind to be aggregated into layers. It is obvious that there must be complete gradation from the random arrangement of minerals of undeformed rocks to the parallel arrangement of minerals of a very cleavable rock. A parallel arrangement is reached at different stages in the development of rock cleavage by different minerals. In the same rock it may be reached by mica, chlorite, and hornblende and not by feldspar and quartz. In a further stage of deformation it may be possessed by mica, chlorite, hornblende, and quartz and not by feldspar. In still more advanced stages of deformation it is acquired by tourmaline, actinolite, grünerite, tremolite, staurolite, sillimanite, andalusite, chloritoid, etc., so far as they receive it at all. Calcite has not been compared directly with these minerals, but unquestionably takes on a parallel arrangement early in the deformation.

The crystallographic or vector properties of the particles of any mineral are parallel only when they have uniform relations with the parallel dimensional axes. This is commonly the case where the particles are either crystals or cleavage plates from crystals that have the characteristic shape and habit of the mineral species represented. In arranging themselves dimensionally such crystals or cleavage plates must necessarily arrange their crystallographic axes. The relations of dimensions to vector properties are uniform in most mica, chlorite, and quartz particles, and in only a small portion of the feldspar particles, while in calcite they show no uniformity whatever. While in a particular mineral these relations may be uniform, in different minerals they may vary. A vector property may be parallel to the greatest dimensional axis in one mineral and to the least dimensional axis in another. Thus the degree of parallelism of vector properties in the rocks with flow cleavage as a whole may be ascertained by listing under each mineral the vector properties corresponding to the parallel-arranged greatest, mean, and least dimensional axes, and seeing how far these properties correspond in all the minerals in the rocks.

While the arrangement of the vector properties of the particles of a cleavable rock is thus subordinate to, and entirely dependent upon, the dimensional arrangement, and while the arrangement of the physical properties with reference to the dimensional axes varies with different minerals, in some of the more common cleavable rocks the net effect of the parallel arrangement of the vector properties of the mineral particles, incidental to and resulting from the dimensional arrangement, may be such as to give the cleavable rock as a whole a definite polarity with reference to these properties—i. e., to give the cleavable rock certain properties for certain directions and other properties for other directions. Experiments on heat, electric properties, cleavage, and hardness of cleavable rocks seem to show some such condition, although it is probably due more to the dimensional than to the crystallographic arrangement of the individual particles. A discussion of these properties in cleavable rocks is outside the scope of this paper. However, attention will be called to one property, the behavior of the cleavable rocks with reference to light, which has been noted in this investigation.

The axis of greatest elasticity $\mathfrak{a}$—the axis affording the easiest vibration of light for rays propagated normal to it—has a position normal to the plane of rock cleavage in the micas, in chlorite, and in talc; within a few degrees of the normal to the plane of rock cleavage in the crystals of hornblende showing triaxial parallelism and in the smaller number of feldspar crystals showing parallel arrangement of their crystallographic properties. In most of the feldspar crystals the axis $\mathfrak{a}$ lies in the plane of the greatest dimensions, while the axis $\mathfrak{c}$ is normal to the plane of rock cleavage. The arrangement of the mean and least elastic axes in some parallel minerals is known, and in others is not known; in the rocks showing flow cleavage as a whole, sufficient data are not yet at hand to warrant any definite statement concerning the uniformity or nonuniformity of arrangement of the mean and least axes. These minerals include the most abundant minerals appearing in the cleavable rocks with uniform crystallographic arrangement. The minerals not mentioned are the porphyritic minerals which are commonly supposed to crystallize either after movement has entirely ceased or near the close of the deformation, such as tourmaline, garnet, staurolite, sillimanite, etc.

In other words the above facts show that so far as the common cleavable rocks have any uniform effect on the transmission of light, due to the optical orientation of the individual particles, they allow the light ray to travel faster normal to the plane of rock cleavage (but vibrating parallel to this plane) than the rays traveling parallel to the plane of rock cleavage. The possible significance of this in its bearing on molecular structure is discussed on pages 97–99.

Repeating the main conclusion, then, the mineral particles in a rock with flow cleavage, so far as they are arranged, have their respective dimensional axes parallel, but only incidentally and partially are their vector properties parallel. The mineral particles have been arranged with their dimensional axes parallel regardless of any influence which the vector properties may have had, except in so far as they modified the dimensions. Even in minerals such as quartz and calcite, in which the physical properties along the principal and lateral axes are strongly differentiated, these vector properties show no tendency to parallelism because they have no uniform relations to the parallel-arranged dimensional axes of the particles. Moreover, the vector properties have no influence in arranging the crystal, where there are no dimensional differences in the principal axes. When two of the three principal dimensional axes of a particle are of the same length, so that there can be said to be no parallel dimensional arrangement of such axes, the vector properties show no parallelism, although in the absence of dimensional control they would have an opportunity to show any influence they might have. For instance, the vector properties lying in the plane of the mica cleavage are not parallel, in spite of the fact that the length and breadth of these plates are not so far different, but that the vector properties, had they had any influence, could have succeeded in arranging themselves without violating the principles of dimensional control.

CHAPTER II.

THE OBSERVED RELATION OF SECONDARY ROCK CLEAVAGE TO THE PARALLEL ARRANGEMENT OF MINERAL PARTICLES.

In the rocks with secondary flow cleavage examined during this investigation, which are believed to be fairly representative of such rocks in general, a plane, or surface, of cleavage has been observed to be uniformly parallel to the greatest and mean, or greatest and least dimensions, or both, or even to the greatest alone, of the parallel constituent mineral particles. This has been observed macroscopically in thousands of specimens, and microscopically in several hundred specially prepared slides. Not only has a cleavage been observed to coincide with the longer diameters of the parallel particles, but it has been apparent that the excellence of such cleavage is proportional to the degree of the arrangement and to the inequality of the dimensions of the particles. In addition to this essential condition of parallel arrangement, another condition, dependent on the first, has been observed to be of great importance—the parallel arrangement of mineral cleavages. This has usually aided the dimensional arrangement, but has rarely tended to cause a cleavage in a plane different from that caused by the dimensional arrangement of the mineral constituents. The characteristic segregation of particles of the same mineral species into layers may develop also planes of weakness that are due to intrinsic strength of the minerals, quite independent of any dimensional arrangement. Minute foldings of parallel-arranged constituents, as in micaceous slates, may yield a plane of weakness parallel to the limbs of the folds (Pl. XIV, *B*), causing a cleavage which has been called in part "false cleavage."

It is needless to say that the agreement of secondary flow cleavage with parallel mineral arrangement, above emphasized, is not a newly observed relation. It has been described and noted by so many geologists that the coincidence of the two structures has been accepted as almost self-evident. Yet, as will be shown in Part II, there is a cleavage, here called fracture cleavage, which is independent of such a parallel structure, and largely because of this certain geologists have concluded that all cleavage may be independent of a parallel arrangement of minerals. A comparison of cleavage independent of a parallel arrangement and cleavage dependent upon such an arrangement—in other words a comparison of fracture cleavage and flow cleavage—is made in Part II.

RELATIVE IMPORTANCE OF MINERALS IN PRODUCING FLOW CLEAVAGE.

If the dimensional arrangement of the particles in the secondary cleavage rocks, and the attitude of the mineral cleavage of the particles are known, there are at hand the facts of occurrence necessary to an intelligent discussion of the relative cleavage-producing capacities of the minerals occurring in rocks with secondary cleavage.

Before taking up the detailed discussion, however, it may be well to explain what is meant when it is said that one rock has a better cleavage than another, or that one mineral affords a better rock cleavage than another. In the following discussion excellence of secondary rock cleavage, parallel either to a plane or a line, will be considered as determined by (1) the facility of parting, (2) the evenness of the parting, (3) the number of planes or lines of parting in a given thickness of rock. The extent to which a given mineral contributes these properties to a rock determines its cleavage-producing capacity.

By observation it is known that secondary flow cleavage in rocks occurs parallel to the greater diameters of the constituent particles, or parallel to the mineral cleavages or both. Usually, but not always, they are in the same plane. It is further a matter of direct observation that the perfection of cleavage depends upon the following factors:

Shape and arrangement.—The degree of flatness or elongation of the particles, and their degree of parallelism, is here meant. The greater the difference between the length or breadth and thickness of parallel particles and the better the parallelism the better the cleavage. The shape and arrangement must be considered together, because particles having shapes favorable to the development of cleavage can produce no cleavage unless they have parallel arrangement, and vice versa, particles well arranged produce poor cleavage unless they show marked differences in dimensions.

According to the relative differences between the dimensional axes, the parallel particles may tend to produce cleavage parallel to a plane, to two intersecting planes, or to a line. Where two of the dimensions are not far different and are both greater than the third, the cleavage produced by the parallel arrangement is in a plane; where two are much smaller than the third the cleavage may be parallel to a line; where the three diameters are of different lengths there may be cleavage parallel to the plane of the greatest and mean diameters, and a poorer cleavage in the plane of the greatest and least diameters; that is, normal to the first one. This less perfect cleavage conditioned by the greatest and least dimensions of the particles is what has been called grain, particularly in descriptions of slates.

Thickness.—The thinner the cleavage-making particles the greater the number of planes or lines of parting between or through the minerals possible in a given thickness of rock.

Cohesion, principally mineral.—The cohesion of the particles is the bond by which molecules of like character are held together. Mineral cleavage is a property of cohesion. The cleavage of the particles themselves and its attitude with reference to the plane of the greatest and mean dimensional axes help to determine the perfection of rock cleavage. The more nearly parallel to the greater dimensions of the particle, and the better the mineral cleavage, the better the rock cleavage produced. Usually, but not always, the mineral cleavage is parallel to one or both of the greater dimensions.

Adhesion.—The adhesion of the particles is the bond by which molecules of unlike character are held together. Where adhesion is less than cohesion, the less the adhesion the better the parting. Where adhesion is greater than cohesion, parting occurs within the particles by overcoming cohesion, and variation in adhesion has no effect on cleavage.

Abundance.—The more abundant a good cleavage-producing mineral is and the more area it occupies in the plane of its greater diameters the better the rock cleavage produced. Aggregation of good cleavage-giving particles into layers may give a good cleavage in such layers, but may leave intermediate layers with a poor cleavage or with none at all. This applies especially to the coarser rocks (schists). It is well known that fine-grained slates, yielding the easiest and most even planes of parting, show no marked concentration of their different cleavage-giving minerals into layers.

Below an attempt is made to indicate the extent to which these factors are applicable to individual minerals, and to determine the relative importance of the minerals as cleavage producers. The cleavage-producing factors are discussed in the same order as above.

MICA.

Shape and arrangement.—The particles have a ratio of greatest or mean diameter to thickness averaging perhaps 100:16, which is the greatest difference found in any of the cleavage-making minerals. They have a strong tendency to parallelism. The greatest and mean diameters do not show any uniform differences in dimensions, and hence the only cleavage produced by the parallel arrangement is parallel to the plane of the mean and greatest diameters.

Thickness.—The thickness of the particles in the rocks examined varies from about 0.01 to 0.40 mm., but averages perhaps 0.15 mm., giving a great number of mica plates and of possible planes of parting in a given thickness of rock.

Cohesion.—Mica has perfect mineral cleavage strictly parallel to its greater dimensions. It is the only important cleavage-giving mineral in which this relation holds, unless chlorite and talc be here included. The cohesion of the cleavage laminae is probably less than in any other mineral with which the mica is commonly associated in a cleavable rock, and usually less also than its adhesion with other minerals. As a result the parting in a rock containing mica is likely to be caused by the separation of the mica plates along their cleavage.

Adhesion.—As stated above, the adhesion of the micas to other particles is usually greater than its cohesion along its own cleavage planes, so that parting seldom occurs between micas and adjacent minerals. When concentrated into the layers the adhesion of the separate crystals of mica may be less than the cohesion of their cleavage, but as the shape of the separate crystals is that of cleavage plates the adhesion in this case might as well be called cohesion. Whether the parting be through the individual micas or between them the parting planes of rocks with secondary rock cleavage containing mica show mica as a dominant constituent.

Abundance.—Mica is very abundant and widespread in the rocks with secondary cleavage. In the rocks with coarser cleavage it has a tendency to be concentrated into layers, which are usually continuous and large in area. In the slates this tendency is slight.

When considered with reference to all of these factors mica is found to be a good producer of rock cleavage, affording great facility of parting parallel to a plane, and causing even planes of parting and a large number of possible planes of parting in a given thickness of rock. Indeed, as will be seen later, mica is probably more important as a cleavage producer than all other associated minerals combined.

HORNBLENDE.

Shape and arrangement.—The ratio of the length to the shortest diameter varies between 100 : 20 and 100 : 25. The ratio of the two shorter diameters is about 100 : 60. The long axes are commonly parallel to one another, and in these cases it is not uncommon to find a tendency for the least and mean axes also to be parallel. In other instances the longer axes are not parallel, but lie in the same plane, and the mean and least axes may not be parallel. In the first case the rock cleavage is almost anywhere in the zone parallel to the long axes, although when the least and mean axes are arranged, probably it is a little better in the plane of the greatest and mean axes than in the plane of the greatest and least axes. If the effect of their concentration into layers is disregarded the parallel hornblendes themselves tend to produce a linear parallel type of cleavage rather than a plane parallel type. There is an axis of cleavage rather than a plane of cleavage. Where the hornblendes have their longer diameters parallel to a plane and not to each other the tendency to parting may be only parallel to this plane.

Thickness.—The smallest diameter in the rocks examined varied from about 0.03 to 0.20 mm.

Cohesion and adhesion.—Hornblende has good prismatic cleavage in two planes inclined at about 28° to the plane of the greatest and mean dimensional development. Where the hornblende particles lie with all three dimensional axes respectively parallel, the prismatic cleavages are inclined 28° to the plane of cleavage produced by the dimensional arrangement. The hornblende cleavage therefore assists but little in producing a parting parallel to this plane. It may, however, and probably does, have an effect in producing the linear parallel type of cleavage, just as do the normal crystal dimensions. The cleavage is parallel to the unit prism faces and produces forms identical with the normal crystal outlines. It is hard to determine whether the parting is more easy around the particles than through their cleavage. The resulting forms are practically the same. The glistening cleavage surface shown on fresh fracture would seem to indicate that the fracture has been through the mineral cleavage planes to some extent at least, and when examined with a lens of high power the hornblende crystals are seen to have a grooved and irregular surface. Whether the parting is through or around the hornblendes, the fractured surface has irregularities which probably correspond roughly to the cleavage surface or to the prismatic shape of the hornblende.

Abundance.—Where hornblende occurs at all in a secondary cleavable rock it is ordinarily in considerable abundance, not infrequently making up much the greater bulk of the rock. There is also a tendency for the hornblendes to lie in layers. However, even where abundant and in layers, they do not occupy all of the area of the potential plane of parting. An average case would be one in which the hornblendes occupy two-thirds of the area, and from this proportion there is gradation to disappearance. While individual hornblendes tend to produce a linear-parallel parting by their shape and cleavage, the effect of their concentration into layers is to make the parting approach the plane-parallel type. In general, therefore, so far as the hornblendes are not concentrated into layers they tend to give a linear-parallel parting; so far as they are in layers they tend to give the plane-parallel type of parting. The common case is perhaps intermediate between these two extremes.[a]

In shape and aggregation, the hornblendes are not so well adapted to give the plane-parallel type of rock cleavage as the micas. They are better adapted by their shape, cleavage, and aggregation to give a linear-parallel type of parting. In either case their effect is much greater than that of quartz or feldspar.

[a] Sp. 40686, sl. 15361, Mesabi district of Minnesota.

QUARTZ.

Shape and arrangement.—The quartz particles described under (1) and (2) on pp. 31–33, that is, the angular and subangular particles due to fracturing, showing all gradations in shape into original, angular, subangular, rounded or crystal-shaped grains, to the slight extent that they are arranged, exhibit a tridimensional parallelism. They may help to produce a rock cleavage in the plane of their greatest and mean diameters, or the plane of their greatest and least diameters (grain or side), or even in the plane of the least and mean diameters, depending upon the relative differences between the dimensional axes. The ratio of the greatest to the least dimensional axes in the rocks measured varied from 100 : 50 to 100 : 100. The lengths of the mean axes varied from almost that of the greatest to almost that of the least. When in slices inclined to the prevailing plane of elongation of the rock mass, the effect of the quartz on cleavage is small. The inclination of the slices to the prevailing cleavage is usually slight and causes only local variations from the prevailing surface of cleavage.

The quartz individuals in the layers and lenses described under (3), on page 33 have a good tridimensional arrangement which may again yield cleavage in the plane of the greatest and mean diameters and in the plane of the greatest and least diameters. But the layers are so thin compared with their length that the cleavage is mainly parallel to their flatness.

In the exceptional spindle-shaped forms described under (3), on page 33 the ratio of length to thickness varies widely. In the slides examined, it averages 100 : 50. The least and mean diameters of these forms are practically the same, so that any tendency to parting which these minerals might condition would be anywhere in a zone parallel to the greatest diameter. However, these grains are phenocrysts and in themselves probably have little effect.

In general, the dimensional inequality of the quartz individuals is so slight, and their arrangement so poor, that their effect as individuals in the production of rock cleavage is small. When aggregated into layers, as described on page 33, their effect may be considerable.

Thickness.—In thickness the quartz particles, of course, vary widely, ranging from large conspicuous phenocrysts to submicroscopic size. A common thickness for the lenses or layers of quartzes described on page 33 is from 0.06 to 0.40 mm.

Cohesion.—The cleavage of quartz is so poor that it probably has no effect on the parting. The cohesion is so great that parting seldom occurs across or within the grains. It is a fact of observation that cleavage surfaces of schists or slates seldom show fracture surfaces of quartz.

Adhesion.—The adhesion with other minerals is usually great. It is again a matter of observation that cleavage surfaces of schists or slates containing quartz seldom show quartz on such surfaces. When associated with feldspar in the "leaf gneisses" it may sometimes appear, but in its common occurrence with mica in the mica-quartz-schists, mica alone appears.

Abundance.—Quartz is one of the most abundant minerals of the rocks with secondary cleavage as a whole, but varies in individual cases from nearly 100 per cent to disappearance. In the coarser schists it has a tendency to aggregation into layers. The layers may be continuous, large in area, and relatively thin and even. The effect on the parting due to the abundance of the particles and to the aggregation of the particles into layers is considerable, notwithstanding the fact that the individual particles are so poorly adapted by their dimensions and arrangement to induce a good parting.

The total effect of the quartz in the production of cleavage is much less than that of either the mica or the hornblende. The parting is less easy. The plane of cleavage is as a rule less smooth, although probably, when the quartz is in the recrystallized layers, it is nearly as smooth as that due to hornblende. The planes of parting are much less numerous for a given thickness. When compared with the feldspars, as will be seen further on, quartz probably has the greater effect on rock cleavage.

FELDSPAR.

Shape and arrangement.—The feldspar with crystal and lenticular outlines, (1) page 35, has in part its longer diameters in the plane of rock cleavage. The diameters in this plane are not respectively parallel. The ratio between the greatest and least diameters varies from 100:50 to 100:75. So far as any rock cleavage is produced by the shape and arrangement it is parallel to a plane. The angular feldspar particles described under (2), on pages 37–39, have a very slight tendency to parallel arrangement. Such as it is, it is probably usually tridimensional. The difference between the greatest and least diameters is not large, 100:40 being an extreme and 100:60 to 100:75 being common ratios. The parting may be parallel to the plane of the greatest and mean axes and also to the plane of the greatest and least axes (grain and side). But in either case, owing to the poor arrangement and the small inequality in the axes, this tendency to parting is very slight. The residual feldspars left after granules have been rubbed off may themselves lie in irregular parallel lenticules (fig. 14). Where the feldspar has been sliced (see p. 38) the longer axes of the slices usually lie at low angles to the plane of rock cleavage (figs. 15, 16, 17). The ellipsoidal and lenticular forms described on page 39 usually have their longer diameters in the plane of rock cleavage. The individuals show a ratio of greatest to least axes of 100:30.

In the cleavable rocks feldspar with random arrangement is probably as abundant if not more abundant than feldspar with parallel arrangement, so that even were the effect of the arranged feldspar considerable, the total effect of feldspar on cleavage due to its dimensional arrangement would be very slight.

Thickness.—The thickness, of course, varies widely, from the largest phenocrysts to submicroscopic size. In the slides examined the arranged feldspars were not thicker than 3 mm.

Cohesion.—As the parallel arrangement of feldspar particles is mainly dimensional and not crystallographic, it follows that the cleavages of the different feldspar particles in general are not parallel and therefore have no uniform effect on the rock cleavage. In exceptional instances the feldspar particles exhibit both dimensional and crystallographic parallelism, and the feldspar cleavages have an effect on the rock cleavage. The good basal cleavage stands at right angles to the greater dimensions of the crystal, and hence to the plane of rock cleavage, to which the greater dimensions of the crystals are parallel. As the greater diameters of the crystals are parallel only to the plane of rock cleavage and not to each other, the basal cleavages of the different crystals, while always at right angles to the plane of the greatest and mean diameters, may be at any angle to one another. The poor macropinacoidal or brachypinacoidal cleavage may stand either normal or parallel to the rock cleavage determined by the dimensional arrangement of the constituent particles, depending upon the nature of the tabular development of the feldspar, whether brachypinacoidal or macropinacoidal. In the former case it is parallel to it; in the latter case it is at any azimuth normal to the plane of the dimensional cleavage, but of course always at right angles to the basal cleavage.

The characteristic arrangement of the basal feldspar cleavage normal to the plane of dimensional cleavage, to which the greater axes of the feldspars lie parallel, has a tendency to produce another rock cleavage at right angles to the rock cleavage conditioned by the dimensional arrangement of the constituent minerals of the rock. The cross cleavage may be well seen in the examination of hand specimens. On the ragged edges of parting normal to the best rock cleavage anywhere in a zone about the specimen, there may be seen numerous glistening cleavage faces of feldspars, many of them undoubtedly basal and some of them pinacoidal; while on the cleavage surfaces of the rock the feldspar cleavages usually do not appear. The basal cleavage of the feldspar would tend to make a better rock cleavage than a rock cleavage produced by the arrangement of the pinacoidal cleavage of the feldspar alone, or by the arrangement of the greater and mean dimensional axes, or both; but the total cleavage-producing effect of the feldspar in any plane is very small compared with that of the other minerals usually present, and thus the cross cleavage produced by the feldspar is usually insignificant compared with the cleavage formed by the dimensional arrangement of the other constituents.

Adhesion.—The adhesion of the feldspar particles to adjacent particles is usually great, probably greater than its own cohesion or the cohesion or adhesion of the particles with which it is associated, with the exception of quartz. As a result feldspars do not appear uniformly on the cleavage face of the schist except where the feldspar is associated with quartz, as in the case of leaf gneisses. In the case of uniform crystallographic arrangement, the feldspar cleavage surfaces may appear as indicated in the preceding paragraph.

Abundance.—Feldspar is one of the most abundant of the minerals of the cleavable rocks. It shows a slight tendency to aggregation into layers, particularly where granulated and in the coarser schists. Where the feldspars have crystal outlines they are usually porphyritic and not concentrated into the planes of rock cleavage; where in layers the effect on cleavage is probably greater than where not so aggregated.

In general, feldspar exerts its effect on rock cleavage in two ways: (1) By its shape, dimensional arrangement, and aggregation it gives a little assistance to other minerals in producing rock cleavage parallel to the greater dimensions of the particles; (2) in the rare cases where feldspar has crystallographic as well as dimensional arrangement the mineral cleavages of the feldspar condition a poor rock cleavage, both parallel and normal to the greater diameters of the particles.

Feldspar and quartz have less effect on the production of rock cleavage than any of the other principal cleavable rock constituents. With respect to the effects of the mineral cleavages on rock cleavage feldspar is more important than quartz. If the effect of an arrangement parallel to their flatness is compared, it seems that feldspar is far less important than quartz. As the arrangement parallel to the flatness is more common than parallelism of mineral cleavage in both quartz and feldspar, it is seen that the general effect of quartz on cleavage is probably more important than that of feldspar. For this reason feldspar has been placed last in the group of principal cleavage-making minerals. In its cleavage-producing capacity it is, however, unique among the minerals in affording rock cleavage in two directions at right angles to each other.

The comparatively slight effect which feldspar has in the production of cleavage is well illustrated in certain feldspathic rocks of the Wausau district of Wisconsin. Here in a number of places the feldspars may be observed to have tridimensional parallelism, yet in breaking out a hand specimen only a very poor rock cleavage, parallel to the basal cleavages of the feldspars, or parallel to the greater dimensions of the parallel crystals may be observed.[a] The same lack of cleavage when the feldspar is well arranged appears in certain of the Archean feldspathic schists of the Mesabi district of Minnesota.

CALCITE.

Shape and arrangement.—The shape of the calcite particles varies in different slides. Where in angular and ellipsoidal grains (p. 41) the ratio of the longest to the shortest axes of the particles varies widely, but 100 : 50 was found to be an average for several slides. The parallelism of the longer axes is not marked, but still a distinct tendency toward it can be detected. The rock cleavage produced depends on the differences in the three dimensional axes and the degree of arrangement, and is (1) parallel to the plane of the greatest and mean diameters—this may be fairly good—and (2), parallel to the plane of the least and greatest diameters—a very poor cleavage.

Thickness.—The thickness varies from submicroscopical to, perhaps, several centimeters.

Cohesion.—The calcite cleavage is rhombohedral. In practically all cases this cleavage is at random angles to the plane of the greatest development of the particles. In one instance the acute angles of the cleavage faces were observed to show a slight and doubtful tendency to lie in the plane of rock cleavage, giving the rhombohedral cleavages an inclination of $37\frac{1}{2}°$ to the plane of the greatest dimensional axes and to the rock cleavage.

Adhesion.—Adhesion of the particles to one another and to other particles is not far different from the cohesion of the mineral along cleavage planes. In the most cleavable marbles the plane of parting is a smooth one and shows but few calcite faces, which indicates that the rock cleavage follows the greater diameters of the constituent particles. Cleavable marbles with a poor cleavage commonly show the calcite cleavage faces on the rock cleavage surface.

Abundance.—Calcite, when present at all, is likely to make up a considerable proportion of a rock, where in subordinate amount there is a strong tendency to be concentrated into layers.

The total effect of calcite in producing rock cleavage measured by the importance of the above factors may be considerable in the cleavable marbles (see Pl. XVI). So far as observed the effect is due entirely to the shape and parallel arrangement. It must be remembered, however, that cleavable marbles are rare when compared with the abundance of noncleavable marbles, which have undoubtedly been under conditions of rock flowage.

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[a] Sp. 5678, Wausau, Wis., cf. Weidman.

CHLORITE.

In general the same statements can be made concerning chlorite that were made above for mica. It has much the same shape. The parallel structure is not so common as in mica, but locally it is quite as good. Chlorite is not classed with the micas because in the typical rocks with secondary cleavage it is certainly far less abundant.

KAOLIN AND TALC.

Talc has essentially the same effect on cleavage as chlorite, but is a rare constituent in the rocks with secondary cleavage as a whole.

TREMOLITE, ACTINOLITE, GRÜNERITE, AND OTHER AMPHIBOLES.

Shape and arrangement.—The particles are commonly greatly elongated. The ratio of the length to the breadth is great. The crystals lie for the most part in random directions, but in some cases are parallel to a plane, and perhaps to a line. Rosettes or sheaf-like aggregates also are common, and the individuals of these aggregates may have a greater development in the plane of rock cleavage than normal to it.

Thickness.—The rosettes are sometimes a foot in diameter, while there is every gradation from this to submicroscopic size. Commonly the crystals are very thin.

Cohesion.—Where the particles are at all definitely arranged, the inclination of the planes of the prismatic cleavages to the plane of the greater diameters is not known; the particles are for the most part too fine to determine this. From the general arrangement of the individual particles it may be stated that it is probable that in general there is no uniformity in this inclination, but that in certain cases, from analogy with the hornblendes, the acute angles of the prismatic cleavage lie in the plane of rock cleavage, in which cases the planes of prismatic cleavages lie at angles of 27° to the plane of rock cleavage. The effect of this factor in the production of the rock cleavage must, however, be practicably negligible because of the imperfect dimensional arrangement of the particles.

Adhesion.—Concerning the adhesion of the particles, it can be said that cleavage surfaces of rocks containing them commonly show the particles on the surface. It is presumable that most of them appear with the normal outlines of the particles, but some of them undoubtedly present the cleavage surfaces of the minerals.

Abundance.—The minerals are not abundant in the rocks with secondary cleavage as a whole. They are, however, often found in the derivatives of calcareous and sideritic rocks. In such rocks they show a tendency toward segregation into layers. This is shown in some cases by the greater development of the rays of a rosette or sheaf-like aggregate in certain planes. Their concentration into layers affords a poor parting.

The total effect of these minerals in the production of cleavage is relatively slight. In some comparatively few instances their parallelism and aggregation are such that a poor parting is produced; but their common occurrence is in blades which interlock to such an extent that parallel planes of parting are not possible, and indeed in places the minerals by their interlocking prevent the parting which the other constituents of a rock have a tendency to condition.

TOURMALINE.

Shape and arrangement.—The crystals are elongated in the prism zone. The ratio between the longer and the shorter diameters varies considerably, a number of measurements of different specimens showing a maximum of 100:20 and a minimum of 100:60. The elongated particles have a marked tendency to lie parallel to the plane of rock cleavage. In this plane there is also to be observed at times a tendency for the crystals to lie with their longer dimensions parallel.

Thickness.—The absolute thickness, of course, varies greatly. The crystals measured vary from 0.1 to 1 cm. in thickness.

Cohesion.—The particles themselves have practically no cleavage.

Adhesion.—In breaking a cleavable rock containing tourmaline, the parting commonly occurs around the tourmaline individuals. The adhesion with the other particles with which it is associated is thus slight.

Abundance.—Tourmaline, even where most abundant, does not form any considerable proportion of a rock with secondary cleavage, and occupies no large area in the plane of possible parting. It also shows little or no tendency toward concentration into layers.

The total effect of the tourmaline on the production of cleavage is slight. Such as it is, it is due to its shape and arrangement and weak adhesion to the adjacent particles. It can produce but few planes of parting, and these planes are very uneven. It may aid other minerals in producing cleavage by preventing fracturing across its longer dimensions.

STAUROLITE.

Shape and arrangement.—Staurolite occurs as tabular individuals, frequently with cross twins. The crystals have a strong tendency to lie with their tabular development approximately parallel to the plane of rock cleavage, although there are many exceptions to this.

Thickness.—The absolute thickness varies widely, from submicroscopic to 2 cm. or more.

Cohesion.—The staurolite cleavage is so poor that parting is seldom or never observed to occur parallel to it.

Adhesion.—The adhesion of the particles to the adjacent minerals is slight, although probably greater than that of garnet or tourmaline. On cleavage surfaces of rocks the staurolites are likely to appear with their natural crystal surfaces.

Abundance.—Staurolite crystals, even where most abundant, occupy but a small proportion of the area of possible parting. They are seldom or never concentrated into layers.

Staurolite has practically no effect in the production of cleavage. Such as it has is due to its tabular development and low adhesion and its tendency to lie with its tabular development in the plane of rock cleavage.

OTTRELITE.

Shape and arrangement.—As shown on pp. 44–45, ottrelite occurs in a variety of forms, but only one shows any parallel arrangement in rocks with secondary cleavage. This appears in flat crystals with a ratio of the greatest to the least diameters varying from 100:50 to 100:35.

Thickness.—The absolute thickness of the crystals measured varies from 0.24 to 0.90 mm.—averaging perhaps 0.45 mm.

Cohesion.—The cleavage of the particles is basal, and corresponds with the longer diameters of the particles. Hence, so far as the crystals have any arrangement, the mineral cleavage is parallel to the plane of rock cleavage.

Adhesion.—The adhesion of the particles to other particles is greater than its own interior cohesion or the cohesion of any of the other minerals with which it is associated except, perhaps, mica. The brilliant basal cleavage is all that usually appears on a surface of rock cleavage.

Abundance.—Ottrelite crystals are not abundant, and show no concentration into layers.

The total effect of the ottrelite in the production of cleavage is practically nothing.

ANDALUSITE.

Shape and arrangement.—These crystals are greatly elongated in the prism zone. The ratio of length to thickness was found from a number of measurements to average about 100:10. The crystals run in every direction through the rock, but there is a greater tendency for them to lie parallel to the plane of rock cleavage than transverse to it.

Thickness.—The absolute thickness in the specimens measured is small, 0.15 mm. being, perhaps, an average.

Cohesion.—The cleavage of the particles themselves is poor, and the rock cleavage is seldom seen to follow the mineral cleavage.

Adhesion.—The adhesion of the particles to the other minerals with which they are associated is usually slight, as shown by the fact that the crystals commonly appear on the cleavage surfaces of the rock containing them.

Abundance.—When most abundant andalusite makes up but a small proportion of the rock, and shows but a slight tendency toward concentration into layers.

Compared with the other subordinate cleavage-producing minerals andalusite may have considerable effect in the production of cleavage on account of its shape, parallelism to a plane, and low adhesion. It has also a negative effect in preventing cross fracture. Its importance is indicated by the number of crystals usually appearing on a cleavage surface of the rock containing this mineral.

SILLIMANITE.

Shape and arrangement.—This mineral occurs as slender acicular crystals, which are sometimes almost hairlike. Average measurements are difficult to obtain as the crystals are characteristically broken across, and it is not possible to determine the limits of the individuals. There is a strong tendency to parallelism of their longer dimensions, either in individuals or in sheaf-like bunches or aggregates.

Thickness.—The absolute thickness is very small, as is indicated above.

Cohesion.—The mineral cleavage parallel to the brachypinacoid is perfect; but the crystals are not flat, and this cleavage probably does not have any uniform relation to the plane of rock cleavage. The crystals are so fine that no direct observations of this relation have been made.

Adhesion.—The adhesion of the particles to other particles is small, as is shown by the fact that the sillimanite commonly appears on the fracture surface of the rock with secondary cleavage in which it occurs.

Abundance.—Sillimanite is not abundant, and forms no considerable proportion of the rocks in which it is present. It is, however, concentrated into layers to a considerable extent.

When the mineral is present in a rock with secondary cleavage, its effect on the parting may be considerable. The effect comes from its shape, parallelism, poor adhesion, and its concentration into layers.

GARNET.

Garnet is isotropic, has no cleavage, and has but a slight tendency to concentration into layers; hence the effect on the production of cleavage is practically nothing.

SUMMARY STATEMENT OF EFFECT OF PRINCIPAL CLEAVAGE-GIVING MINERALS (MICA, HORNBLENDE, QUARTZ, FELDSPAR) ON FLOW CLEAVAGE.

Shape and arrangement.—With reference to the inequality of the dimensions of the fragments the micas stand easily first, hornblende second, quartz third, and the feldspars last. Between the micas and hornblendes the difference is wide; between hornblende and quartz it is still greater; between quartz and feldspar it is little.

The degree of parallel arrangement varies with the inequality of the axes of the fragments; the micas have the best arrangement, while the feldspars have the poorest.

The parallel unequiaxial particles of cleavable rocks tend to cause the best cleavage parallel to the plane of the greatest and mean diameters. In mica there is no uniform difference between the mean and greatest diameters, and hence the mineral affords no other cleavage. In hornblende there is but little disparity between the least and mean diameters, and hence the greatest and least diameters give a cleavage almost as good as that afforded by the greatest and mean diameters. There is an axis rather than a plane of cleavage. In quartz and feldspar the difference between the greatest and mean diameters is usually slight, but when arranged there may be a tendency to produce other cleavages parallel to the plane of the greatest and least diameters (side)[a] and rarely and doubtfully even parallel to the plane of the least and mean diameters (end).

It is to be remembered that all of these minerals may exceptionally occur as porphyritic constituents in rocks with secondary cleavage, in which case there may be no dimensional arrangement.

Thickness.—With reference to the absolute thickness, and hence the number of possible planes of parting in a given thickness of rock, the order on the average is mica, hornblende, quartz, and feldspar, although local conditions may change this order.

Cohesion.—In the effect of its own mineral cleavage one group of minerals—the micas (and chlorite, kaolin, and talc)—stands preeminent. Not only is the cleavage of the micas exceedingly good along one plane, but this plane corresponds exactly with the plane of the greatest dimensional development of the crystals. The mineral cleavage and the dimensional arrangement work together. Next in importance is the hornblende cleavage. The hornblende cleavage aids the dimensional arrangement of this mineral in producing the linear-parallel type of parting. The influence exerted by the feldspar cleavage is relatively slight. Of the two feldspar cleavages one is commonly parallel to the plane of the greatest dimensions, and the other, the best, normal to it. This latter is a conspicuous feature. Feldspar is there-

[a] Such cleavage has been called "false cleavage" by Sharpe.

fore unique among cleavage-producing minerals in affording two cleavages at right angles to each other.

Adhesion.—In general there is great adhesion between the mineral particles, as evidenced by the fact that the minerals appearing on the rock cleavage surface are likely to exhibit their mineral cleavage planes, indicating that parting has occurred within the micas, the hornblende, or the feldspars. Less commonly it occurs between the hornblende and adjacent minerals, or between the quartz and feldspar and adjacent minerals.

Abundance.—As to abundance, no comparative statement can be made. The minerals vary widely in proportion in different rocks. Quartz and the feldspars, however, in general probably make up a greater bulk of the rocks with secondary cleavage than do the hornblendes or the micas. As to aggregation into layers, particularly in the coarser cleavable rocks, the micas are again far in the lead, with hornblende and quartz next, and the feldspars probably last. This gives a better parting but fewer planes of parting in a given thickness of rock. The tendency of all minerals toward concentration into layers rather than toward even distribution is the characteristic feature for the coarser cleavable rocks. For the slates the grain is so fine that this concentration can not be observed.

Mica, then, stands easily first as a cleavage producer. It is more important probably than all the other minerals together, because of the parallelism of its perfect mineral cleavage with the rock cleavage afforded by its greater dimensional arrangement, a condition found in no other mineral. Its cleavage is parallel to a plane. Hornblende stands next in importance, and locally may produce a cleavage nearly as good as that made by the micas. Its effect is to produce either a plane-parallel or a linear-parallel type of cleavage, or some combination of these. Quartz and the feldspars are relatively unimportant compared with the first two minerals. Quartz probably has a greater effect than feldspar, due to its better dimensional arrangement. Feldspar, however, when arranged by recrystallization, exerts through its own cleavage a unique influence in producing cross rock cleavage.

CHAPTER III.

THE PROCESSES THROUGH WHICH THE SECONDARY PARALLEL ARRANGEMENT OF MINERALS IS BROUGHT ABOUT.

The production of secondary parallel structures has been observed to be associated with the deformation of rocks. A consideration of the factors of rock deformation in general will enable us to see more clearly the nature of the particular kind of deformation which is accompanied by the production of parallel structures.

As has been shown by observation and experiment the principal factor in the deformation of rocks is differential pressure. The statement is almost axiomatic. For the present purpose, it is immaterial whether the pressure be produced vertically by the superincumbent weight of strata, horizontally by the lateral thrust due to the crustal shortening of the earth, by the intrusion of igneous rocks, by increase of temperature, or by any combination of these or other causes. Other factors affecting the manner of rock deformation are the physical and chemical properties of the constituent minerals, the original arrangement of the minerals, and the conditions of temperature, moisture, and time under which rocks are deformed. According to the relative importance of these factors, rocks yield to pressure in different ways. The adjustment may be accomplished by coarse fracturing and differential movement; by minute slicing; by fine fracturing extending only through the individual mineral particles of the rock, called granulation; by chemical change or redistribution, called crystallization or recrystallization; by the molecular-mechanical change of gliding along crystal planes; by parallel rotation of its constituent parts, without either molecular change or fracturing; or by any combination of these methods. Where the rock has permanently changed its form without losing its integrity, the molecular attraction being strong enough to hold the particles together, it is said to have flowed. All of the processes through which the rock may change its form may be effective in rock flowage, the essential limitation being that fracturing must not be so extensive or so preponderate over the other processes as to disintegrate the rock.

One of the common results of "rock flowage" is a parallel arrangement of the mineral constituents of the rock, giving it a "flow" cleavage. So common is such an arrangement in rocks which have been deformed by "flowage" that the existence of a parallel arrangement is commonly accepted as proof that a rock has flowed. For those not accepting this as proof, however, there is other evidence as is noted on pp. 102–108.

Where rock deformation occurs by slicing a "fracture cleavage" may be developed independent of any parallelism of mineral constituents. This occurs through the development of incipient fractures or the welding or cementation of parallel fractures, yielding parallel planes of weakness.

The conditions under which fractures are prominent may be observed near the outer part of the lithosphere. The conditions under which fractures are less extensive or subordinate to other processes of deformation are believed to exist at greater depth. Hence for convenience in discussion, the outer part of the lithosphere has been designated by Van Hise[a] the zone of fracture, while the deeper zone where rocks are deformed without fracture more extensive than granulation, has been designated the zone of rock flowage. It is readily understood that there is no sharp and regular plane of demarcation between these zones, but everywhere gradation and irregularity. For some rocks the zone of fracture extends to great depth; for others the zone of flowage extends to the surface. Local physical conditions may also cause these variations for the same rock. An attempt has been made by Van Hise to determine, on a basis of observed fact and mathematical deduction, the approximate depth to which the zone of fracture may extend, the result obtained being about 12,000 meters for the hardest rocks. Below this depth fractures probably do not exist; the rock flows when deformed. Thus flow cleavage, as a result of rock flowage, is essentially a phenomenon of the deep-seated zone of flowage. It appears at the surface through the removal of the overlying rock by erosion.

In this chapter flow cleavage will be discussed. The consideration of fracture cleavage is deferred to Part II.

SECTION I. GENERAL ACCOUNT OF POSSIBLE PROCESSES OF ROCK FLOWAGE YIELDING PARALLEL ARRANGEMENT.

It follows from the foregoing that the processes resulting in the change of form in the rock during flowage must also be the ones which in some way result in bringing about the parallel arrangement of the mineral constituents. These processes in their relation to parallel arrangement are:

(1) Crystallization and recrystallization, resulting in flattening of

[a] Van Hise, C. R., Principles of North American pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 589–603.

old mineral particles and growth of new ones in planes of easiest relief. These processes might conceivably also result in segregation of minerals of the same kind into bands, with or without parallel arrangement of the constituent particles, and might thus afford a parallel parting due to differing tenacity in or between different bands.

(2) Gliding along definite planes in minerals, resulting in flattening of the mineral particles. Gliding, crystallization, and recrystallization are the only processes which have been suggested to explain the flattening of mineral particles without fracture.

(3) Rotation of particles, of whatever origin, toward a parallel dimensional arrangement.

(4) Granulation without rotation may produce a parallel arrangement of the mineral constituents by leaving residual parallel grains and by breaking the particles into slices which have a rude parallelism. Through the crystallization of other constituents, or through the cementing of such fractures by infiltration of mineral material, or through the uniting of the parts due to molecular attraction under pressure, the rock may retain its integrity.

The nature of each of these possible processes will be considered, after which will be taken up their relative importance in the arrangement of individual minerals and in the arrangement of the particles of the metaclasic rocks as a group.

CRYSTALLIZATION AND RECRYSTALLIZATION.

Crystallization and recrystallization include the growth of old crystals, fortunately orientated, in the plane of easiest relief, and the production of entirely new crystals with their greater dimensions in the same plane.

Attention has been paid to this subject by many investigators, but the latest and fullest discussion, especially in application to the development of secondary rock cleavage, has been made by Van Hise,[a] whose work is briefly summarized below.

Crystallization and recrystallization are brought about by solution and deposition of minerals principally through the agency of water.

Water has long been known to have the power of taking minute quantities of mineral matter, including silicates, into solution. At ordinary temperature this process is exceedingly slow, yet it occurs to an appreciable extent; at higher temperatures it takes place much more rapidly. Barus has shown 180° C. to be the critical temperature for glass. At higher temperatures glass is dissolved in water very rapidly—from 180° to 220° C. it remains in a colloidal state, and beyond 220° it is in clear solution. In lowering the temperature the glass goes through a reverse series of changes. Temperatures as high

[a] Van Hise, C. R., Bull. Geol. Soc. America, vol. 9, 1898, pp. 269-328; Mon. U. S. Geol. Survey, vol. 47, 1904.

as 180° C. exist in the crust of the earth at a depth of about 5,000 meters, with the normal temperature gradient, though in regions of volcanic or dynamic action this temperature may exist near or at the surface. Barus has shown the solution of glass to be accompanied by a diminution of the volume of the glass-water system, and probably also by the development of heat. Vice versa, the deposition of glass from the glass-water system is accompanied by increase in volume of the glass-water system and by absorption of heat. Pressure and temperature therefore have an important influence on the solution and deposition of the glass. If refractory glass behaves in this way, minerals in rocks are likely to yield to similar changes even more readily.

All rocks contain water, in supercapillary, capillary, and subcapillary openings. Under varying conditions of high temperature and pressure of the lower zone of flowage now under discussion this water must be active in taking mineral material into solution and depositing it. The water takes the material from the mineral particles and deposits it in an unstrained crystal form, either on the parts of the same particle or elsewhere. There is probably no extensive migration of material, for the openings are minute. If an entirely new mineral or crystal is developed the process is called crystallization; if an old particle is regenerated or changed in form the process is called recrystallization. However, there is no sharp line between the two. The material for crystallization may come from minerals close at hand, and thus, so far as the rock as a whole is concerned, the process is really recrystallization. In the following the two terms are separated when practicable, but in many cases it seems advisable to use the term recrystallization to cover the general process of molecular change for the rock as a whole.

Pressure is the dominant factor. If the pressure on a solution near the solubility temperature of the solute increases, solution takes place; if it decreases, deposition occurs. In a rock undergoing deformation, pressure on capillary and subcapillary filaments of water probably varies from time to time and from place to place. It must vary in different-sized openings. This may result in crowding the water out of the places of great pressure and concentrating it in places of less pressure. If near the critical temperature, deposition may be supposed to take place wherever the lessening pressure, causing supersaturation, allows it.

On the other hand, with the pressure near the critical point, changes of temperature will cause solution and deposition. A rise of temperature may enable the water to take more material into solution, while a fall of temperature may cause supersaturation of the solution and consequent deposition. Different parts of the same rock mass may be at different temperatures, and solutions moving from place to place almost certainly find conditions of temperature favorable for depositing their load; also, the temperature at the same point may vary from time to time.

A third factor in influencing deposition is the selective influence of the solid mineral particles with which a solution comes in contact. There is a tendency for minerals to select from solution material like that of which they are composed and add it to themselves in crystallographic continuity. Of course, some minerals, under given conditions, have much greater power in this way than others; such are those favored by possessing a mineral habit, cleavage, or density best adapted to the conditions of existing pressure. Certain particles fortunately oriented may grow or survive, while adjacent particles, not so oriented, may be destroyed.

Another factor affecting the solution and deposition of mineral material is the physical condition of the mineral particles. If the minerals with which water is in contact are in a state of strain, and thus have energy potentialized in them, solution is known to be greatly accelerated. As the mineral material after deposition is not in a state of strain the process of recrystallization obliterates evidences of strain. If a strained condition of the minerals accelerates solution a condition of no strain in the mineral in contact with the solution does not accelerate solution, and thus may be of negative assistance to deposition. The strain effects present in a mineral are probably dependent largely on the position of the mineral crystal with reference to pressure, minerals unfavorably situated being most strained and hence likely to be the first to go into solution.

With the proper combination of the above factors old mineral particles grow and new particles develop with their greater diameters in the directions of relief from pressure. The relations of these directions of relief to pressure are discussed on pages 109–118.

The process of molecular change by crystallization or recrystallization is thus one of solution and deposition of mineral material by the water contained in rocks. In its accomplishment much or little water may be used, but an extremely small amount only is necessary. Also the amount of material in solution may be much or little, but it is usually so small compared with the adjacent solid minerals that the rock throughout the process of its change of form by recrystallization is essentially a solid. Indeed, there is evidence that changes between solid particles may occur, to a yet unknown extent, without the intervention of water, but the important process is believed to be as above described.

Crystallization or recrystallization under rock deformation tends to result in the condensation of chemical systems—that is, the minerals so developed during rock flowage usually have a higher specific gravity than the average of the minerals from which they are derived.

Thus far Van Hise's discussion has been followed in the main. Below are discussed certain additional features of the subject which have appeared during the investigation here reported.

Criteria for determining crystallization or recrystallization.—Criteria for determining the probability of crystallization or recrystallization of a given mineral during rock flowage may in part be deduced from what has been said on the principles of recrystallization, but in large part they have been brought to mind by a study of individual minerals during this and other investigations. They are as follows:

(1) The conditions of depth, temperature, moisture, or time under which the rock is deformed. Often important evidence can be obtained which will show this, and thus determine the presumptive importance of recrystallization. The presence of water is usually an essential condition.

(2) The nature of the rock itself as showing the probability of its yielding by recrystallization, rotation, or fracture.

(3) The mineral associations and the character of the mineral itself. Not infrequently the mineral is known to be of a secondary nature from its characteristics of color, zonal growth, etc.

(4) Presence of minerals in a metaclasic rock which were not present in the rock from which the metaclasic rock can be shown to have been derived.

(5) The occurrence of minerals with their greater diameters at right angles to an original structure—such as bedding—which does not show sufficient deformation to warrant the assumption that the minerals at right angles to the bedding reached their position through rotation. Such minerals could not have been deposited in this position; they could not have been rotated to this position; development in situ is the only alternative.

(6) The shape of mineral particles in the rocks with secondary cleavage, as compared with the shape of those in original igneous rocks.

(7) The manner of contact of the minerals. In the micas, for instance, the laminæ of one crystal feather out diagonally against those of another, giving close diagonal contact, which could be produced only by molecular adjustment.

(8) The size of the particles. Crystallization or recrystallization has a tendency to increase the size of the grain (see pp. 76–78). If the grain is coarser than seems necessary for the amount of deformation the rock has undergone, or coarser than in the original rock, crystallization or recrystallization, the only constructive processes known, must be the cause. This evidence is decisive in many cases, as for instance, in a coarse schist derived from a mud stone.

(9) Better than the size of grain is the evenness of grain. It is shown (pp. 71–78) that recrystallization combined with granulation has a marked tendency to produce an even grain.

(10) The lack of strain effects commensurate with the deformation shown by the rock as a whole or by adjacent minerals. When strain effects are present in most minerals they are conspicuous; when absent or slight this is easily determined.

(11) The complete parallelism of minerals, or, what amounts to the same thing, the lack of bending or breaking due to interference of particles, which would necessarily be in evidence if the particles had been much rotated.

(12) Recrystallization has a tendency to segregate minerals of the same kind into bands, in this showing great similarity to original flow structure.

Crystallization or recrystallization accompanied by rotation.—Crystallization or recrystallization is usually accompanied by rotation of the particles, as will be shown in the discussion of the relations of parallel structure to pressure (pp. 109–118).

So-called flattening of particles in situ largely a process of recrystallization.—It is believed that the so-called "flattening of particles in situ," so frequently cited, occurs in most cases through the process of recrystallization above described. But gliding along mineral cleavage planes may be partially responsible in some cases.

ROTATION.

The part which rotation plays in producing a parallel arrangement of mineral constituents during deformation is most difficult to determine.

Effectiveness of rotation in bringing about an approach to parallelism of mineral constituents in rocks with secondary cleavage may depend upon the conditions of temperature, moisture, pressure, and speed under which the rock is deformed and upon the characteristics of the particles themselves—their size, shape, and manner of aggregation. The interrelations of these two factors, determining the rotation of a mineral particle, are exceedingly complex.

When differential pressure is applied to the complex mass of particles forming a rock, and the rock flows, there is a tendency to a rotation of all particles which are not already arranged with the best possible attitude toward the pressure there acting—i. e., on all particles on which couples are effective under the given stress conditions. This applies to all particles, whether original, recrystallized, or recrystallizing.

If there is freedom of movement of the particles, sufficient rotation is likely to cause approach to parallelism. In a soft, plastic clay which is deformed at the surface under conditions where recrystallization is not possible the particles have such freedom of movement that approximate parallelism of the particles may be reached, but this requires a very considerable amount of shortening of the rock mass. Also in the deep-seated zone where rock deformation is brought about mainly by recrystallization, considerable freedom of movement may be allowed certain particles by the process of recrystallization affecting the particles of the rock unevenly. In an ideal case where the particles have no interference the degree of parallelism reached by a certain amount of rotation may be indicated in figs. 20 and 21, taken from Harker. If a circle with a definite number of radii representing the greater diameters of original particles be compressed into an ellipsoid with its shorter diameter one-fourth the length of the diameter of the circle, the radii making an angle of less than, say, 10°, with the plane of greatest elongation will be twelve times the number within the same angle in the undistorted form.

The shape of the minerals also is likely to have some effect on the freedom of movement. One would suppose that in a complex of long narrow crystals there would be more interference in rotation than in a complex of short, stumpy crystals. If this is the case the crystal best adapted to a parallel arrangement under differential pressure—that is, one with great differences in dimensions—is not adapted for rotation into such parallel arrangement. Suppose, for instance, that the long, slender hornblende crystals in a rock had random arrangement, and the attempt were made to rotate them toward a common plane or line. It may be clearly seen that long before approximate parallelism is reached the crystals will mutually interfere, and then because of unequal transverse support they are likely to be broken in their further movement. This fact of necessary interference is dwelt upon here because later it will be shown that many long, slender crystals which now lie parallel in schists could not have been rotated to this position because they do not show such interference effects. Where the slender crystals are few, or are so arranged that they will not interfere, rotation may be effective in bringing about their parallelism, as has been shown during this investigation.

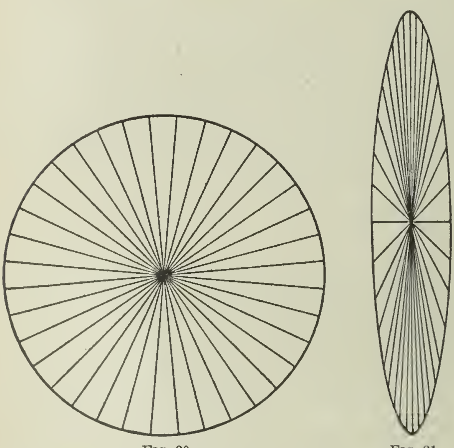

FIG. 20. FIG. 21.

FIGS. 20 and 21.—Diagrams showing the rotation accompanying a given amount of shortening. After Harker, Rept. 55th Meeting Brit. Assoc. Adv. Sci., 1885, p. 822.

The size of the particles may also have an effect on the degree of parallelism reached by rotation. With a given amount of deformation under certain conditions the smaller the particles affected the more will they be rotated. Figs. 22, 23, 24, and 25 illustrate this.

If a particle with the diameter X Y is rolled between two plates P P′, until the one plate is past the other to a distance S S′, the diameter X Y, which was originally normal to the plates, as shown in fig. 22, will have the position shown in fig. 23. Now roll a particle of smaller size with the diameter X′ Y′ (fig. 24) between two plates until the upper plate is past the lower plate the same amount as in fig. 23. In this case the diameter X′ Y′ of the smaller particle will rotate to a much greater angle with its original position than did the diameter of the larger particle. If the circumference of the first particle is 2 inches and that of the second 1 inch, a movement of one-fourth of an inch

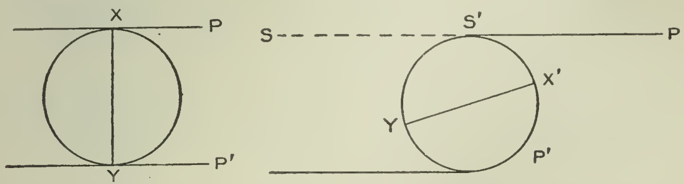

Fig. 22. Fig. 23.

FIGS. 22 and 23.—Diagrams showing angle of rotation of large particle under differential movement amounting to SS′.

will revolve the axis of the large particle 45°. A similar movement will revolve the axis of the smaller particle 90°. Therefore the amount of revolution which a particle undergoes in a given amount of movement is inversely as its circumference. This has been shown experimentally in clay mixed with particles of mica. With a given amount of movement it has been shown that the finer the particles of mica so mixed the more nearly parallel they are. Granulation produces smaller particles and hence may aid rotation in bringing particles into parallelism.

It is thus seen that rotation is likely to be effective so far as there is freedom of movement, so far as the particles are equidimensional,

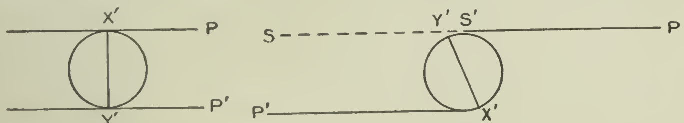

Fig. 24. Fig. 25.

FIGS. 24 and 25.—Diagrams showing angle of rotation of small particle under differential movement amounting to SS′.

and so far as they are small. It will be shown (pp. 109–118) that rotatory stresses are always present in the strains commonly occurring in rocks, and that all particles, whatever be their origin, so far as they are not already in the best possible attitude toward pressure, or normal to this position, are likely to feel the effects of these strains.

For rotation the obvious criteria are as follows:

(1) The presence of strain effects, which are certainly more characteristic of rotation than of recrystallization. One of the most characteristic of these is angular outlines, indicating that the shape is due to

granulation. Where the particles are angular and clearly due to the granulation of larger particles it is certain that any parallelism of their longer diameters that is observed in the rocks with secondary cleavage is due to rotation, as no other process is possible in such a case. In such rocks the granulation of larger particles can be observed in all its stages, and accompanying the granulation may be seen all stages of rotation of the fractured particles. These granulated particles are not markedly unequidimensional, and hence there is usually little interference. The occurrence of angular particles apparently due to granulation is one of the best criteria observed for determining that rotation has occurred. The lack of angular character, however, is not evidence that rotation has not occurred.

(2) The absence of positive evidence of recrystallization. The reverse condition, the presence of evidence of recrystallization, does not show that rotation has not occurred.

GLIDING.

Certain crystals may change their form under pressure by differential movements along "glide" planes without open fractures.[a] The glide planes frequently follow the mineral cleavage. After the movement the glide planes may be planes of secondary twinning. Movements with minute fracturing along twinning or cleavage planes of minerals have also been called gliding by some writers. They are considered in this paper under "slicing." Gliding is accompanied by a minute change of form. For only a few minerals has this change of form been shown to have any considerable value. The best gliding observed is found in calcite, and the process will be described in connection with that mineral (pp. 88–90).

The principal and almost the only criterion for the detection of gliding is the presence of repeated twinning and slip planes, sometimes giving a reedy or fibrous structure. Both granulation and recrystallization destroy these gliding planes, and if abundant evidence of either of these processes is present, they may hide the evidence of gliding.[a] For this reason the part gliding has played in flattening and elongating mineral particles can not be determined certainly from a study of the metaclasic rocks themselves. Its relative importance may be argued only from the presence of evidence of crystallization adequate alone to explain the observed facts. Experiments by Professor Adams still in progress are likely to show to what extent gliding may be effective.

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[a] Adams, F. D., Experimental investigation into the flow of marble: Philos. Trans. Royal Soc. London, ser. A, vol. 195, 1901, pl. 24, fig. 4. Mügge, O., Ueber die Plasticität der Eiskrystalle: Neues Jahrbuch für Mineral., etc., vol. 2, 1895, pp. 212–228.

GRANULATION.

This process probably is most effective in its assistance to rotation and recrystallization (p. 76), but even where recrystallization or rotation is practically absent, it may still produce a very imperfect parallel structure.

Granulation may leave residual flattened particles. When a rock is put under pressure and fracturing occurs, the fractures are usually highly inclined to the greatest pressure, as shown on p. 112. Probably where the material is not confined on the sides, the fractures for the most part have positions inclined less than 45° to the greatest pressure. However, where the material is not ideally brittle or is confined on all sides it has sometimes been observed that the fractures tend to take positions at angles greater than 45° to the greatest pressure, carving the grains into flattened cones or lenticular forms, with diamond-shaped cross sections. It may be that the flatness of the residual grains is in part really due to the minor recrystallization or gliding of the particles and not to the direction of fracture. Such flattened particles, when formed by fracture without the aid of the processes above outlined, will have their greater dimensions parallel, and so this process must be mentioned as one of the possible ones in the production of parallel structures. It is simply one of the results of granulation.

A better parallel arrangement is developed where the granulation occurs mainly along one set of shearing planes rather than along two intersecting sets, taking off slices or minute granules from the side of the original particles and leaving the remnant of the particles as thin, ribbon-like fragments with parallel arrangement.[a]

While granulation usually fractures particles in such a way that the resulting smaller particles have no great differences in dimensions, it has been observed that the material broken from the particles is sometimes in slices whose long dimensions follow the directions of fracture (figs. 15, 16, and 17). The length of such slices is not infrequently 5 or 6 times the thickness, although a ratio of 3:1 is more common. At the time and place of breaking these particles may be arranged with their longer diameters at angles 45° or less to the general plane of rock cleavage. The special kind of granulation that results in parallel slices is for convenience of discussion called "slicing" in this report.

The phenomenon of slicing may be particularly well seen in a mineral which itself has a good cleavage to control the direction of slicing. In hornblende, for instance, slicing with little or no rotation has been observed to divide a large particle into a number of thin ones lying with their greater diameters at a low angle to the plane of

[a] See discussion of Adams's anorthosite, p. 37.

schistosity (fig. 7, p. 30). Where slicing follows the mineral cleavage, stages of its gradation into gliding are to be observed.

Assistance of granulation to recrystallization.—Granulation forms small particles and brings about a state of strain in particles, both of which are favorable to recrystallization. With a given mass the finer the subdivision the greater the surface. The finer the subdivision, therefore, the greater the reaction, ceteris paribus, between mineral and solvent. Also, the deformation leading up to granulation induces a state of strain in a mineral in which energy is potentialized. Minerals thus strained are attacked much more readily by solvents than minerals not so strained. A further and important assistance is rendered by the development of heat due to the mechanical crushing.

Assistance of granulation to rotation.—Granulation aids rotation in two ways. It produces smaller particles and allows greater freedom of movement. So far as slicing occurs, the greater dimensions of the slices just after granulation may lie at angles not larger than 45° to the plane of rock cleavage, from which position a comparatively slight amount of rotation will carry their longer diameters into the plane of rock cleavage. Evidence of such rotation frequently accompanies slicing. In many observed instances the fractures are at even smaller angles to the plane of cleavage, and a small amount of rotation has induced a close approach to parallelism.

THE COMBINED EFFECT OF RECRYSTALLIZATION AND GRANULATION ON SIZE OF GRAIN.

As a matter of observation recrystallization tends to increase the size of the particles in a rock mass undergoing rock flowage; but to varying extents in particles of different mineral species. The increase in size comes from the fact that small particles present greater surface per unit volume for the action of solvents than larger particles, and the material of the smaller particles goes into solution and is ultimately added to the larger particles because of the "surface tension which exists on the boundary surfaces between solids and liquids, as on those between liquids and gases—the so-called free surfaces of liquids. This tension acts so that the surfaces in question are reduced in size, with the consequent enlargement of individual crystals (the total amount of precipitate remaining practically unaltered), i. e., with the coarsening of the grains."[a] Granulation tends to subdivide the particles of a rock mass undergoing rock flowage, but to varying extents with different minerals. Other things being equal, the larger particles of the rock are likely to feel more of the differential pressure, and to be granulated to a greater extent than the smaller ones. Whether acting separately or together, recrystallization and granula-

[a] Ostwald, W., The Scientific Foundations of Analytical Chemistry, Macmillan & Co., London, 1895, p. 22.

tion tend to cause a uniformity in the size of particles of the same mineral species in a rock, a fact of direct observation in cleavable rocks. But in a given rock the uniform size of the particles of one mineral species thus produced is not the same as that of another mineral species.

This difference in size of grain in different mineral species results not only from difference in mineral habit, but from the fact that recrystallization and granulation affect different minerals to different degrees. In some minerals, under given conditions, recrystallization or granulation occurs, one almost to the exclusion of the other, and in other mineral particles both processes occur. The size of grain depends upon the balance obtained between the two; in other words, it is the net result of a contest between the constructive process of recrystallization, tending to produce larger grains at the expense of smaller ones, and the destructive process of granulation tending to break down the larger particles. The recrystallization of micas and hornblende, without granulation, produces a characteristic uniformity of grain for each of these minerals. Granulation of quartz and feldspar particles, without recrystallization, produces a characteristic uniformity of size of grain for each. Granulation and recrystallization, acting together on quartz and feldspar, tend to cause uniformity of size of grain in each. As would be expected, the mineral particles showing evidence of recrystallization alone, such as mica and hornblende, are larger than the ones in which the process of granulation or of granulation and recrystallization combined have been effective, such as quartz and feldspar.

It should be remembered that rocks with secondary cleavage are composed very largely of mica, hornblende, quartz, and feldspar, and for the most part of two or three of these minerals, and hence there are usually, as shown by observation and measurement, but two or three characteristic sizes of grains, giving, in connection with parallel arrangement, a striking impression of uniformity of grain, in marked contrast to the grain observed in many of the rocks before rock flowage has developed a cleavage in them.

After rock flowage has ceased it not infrequently happens that recrystallization continues or again begins, and then the tendency of large grains to develop at the expense of small ones is not opposed by the tendency of granulation to break down the larger particles as they form. To this condition may be ascribed the porphyritic crystals frequently seen in cleavable rocks which have developed apparently without regard to the prevailing cleavage in the rock, and show included in them other constituents of the rock with a dimensional arrangement parallel to the plane of rock cleavage (Pls. III and XIII). The principal cleavage-giving minerals—mica, hornblende, quartz, and feldspar—may be sometimes observed to develop under these conditions. The minerals characteristic of cleavable rocks, but not having any great effect on rock cleavage—such as garnet, tourmaline, chloritoid, andalusite, chiastolite, staurolite, etc.—are known to develop commonly under such conditions and only rarely during rock flowage.

SECTION II. RELATIVE IMPORTANCE OF PROCESSES OF ARRANGEMENT IN INDIVIDUAL MINERALS.

MICA.

The origin and parallel arrangement of mica plates in the micaceous schists, slates, and phyllites are believed for the most part to be the result of crystallization or recrystallization, for the following reasons:

Micaceous schists are rocks which are known in many cases to have been in the zone of rock flowage, under conditions of high pressure and heat, and with a considerable water content; all of these are conditions favorable to the development of mica by crystallization or recrystallization. Mica certainly is not a characteristic mineral of the belt of weathering.

The micaceous schists and phyllites are very common products of the alteration of water-bearing feldspathic sandstones or graywackes and shales or muds, originally containing little mica, and they are also the result of the metamorphism of various igneous rocks with or without mica as an original constituent.

The occurrence of mica in large flakes in schists derived from rocks originally containing small flakes or none at all is the most decisive evidence that can be offered of its development by recrystallization.

In certain cleavable rocks derived from sediments the mica plates can be seen to stand at right angles to the original bedding, and this original bedding may not show deformation sufficient to warrant the assumption that the micas now found at right angles to the bedding were originally parallel to the bedding and owe their present positions to rotation. They could not have been originally deposited in this position; they could not have been rotated; the alternative explanation is crystallization in situ.[a] (Pl. XIV, A.)

The common association of the micas in cleavable rocks with secondary minerals, such as garnet, staurolite, etc., well known to be secondary developments by new crystallization, is presumptive evidence that the micas themselves may have resulted from secondary crystallization.

When the original nature of the rock is in doubt, certain features to be observed in the micas of metaclasic rocks with secondary cleavage are evidences of recrystallization. Petrographers sometimes discriminate secondary mica from original mica by criteria of color, shape, or distribution. The micas commonly lack strain effects such as would be

[a] Sp. 14745, sl. 9380, Little Falls, Minn.

expected in minerals of their shape if original and rotated to their present position. They have more uniformity in size and in general a larger size than mica particles in noncleavable rocks. Their manner of feathering out against each other precludes the idea of their rotation as original minerals to this position.

The micas may be found in layers, these layers alternating with quartz layers which have certainly been recrystallized. The association of the quartz and biotite and the nature of the contact of the two minerals are good evidences of their new crystallization (Pl. IX, *B*).

Sericite is a common development in the peripheral granulation of quartz and feldspar, assuming a characteristic parallel position (fig. 26). That the parallel position of the sericite is due to crystallization in situ is scarcely open to doubt.

Rotation of original grains and the retention of the arrangement of favorably orientated original micas probably enter also to a very limited extent into an explanation of the present arrangement of the micas. In a rock with secondary cleavage developed from a rock originally containing mica it is probable that some of the flakes now present were originally present, and have either retained their original positions or have been rotated. The micas lying with their cleavage plates at a low angle to the plane of rock cleavage would be the most likely to be rotated to this plane. Occasionally there may be observed the actual bending of mica plates in a common direction, showing the direction of rotation. In the false cleavage described on pp. 25–26 the parallel mica plates may be seen in various stages of subsequent rotation along certain zones.

FIG. 26.—The secondary development of parallel sericite by crystallization in cracks formed by fracture. (H. 1040 Sericite-schist. Tamus.)

Two other processes may have a slight effect in arranging the micas, gliding and slicing—that is, the differential movement between cleavage laminæ without actual fracture and similar differential movement with fracture. It is doubtful whether mica shows to any extent true gliding in the cleavable rocks, but it is certain that many mica plates owe their arrangement to the slicing of larger mica plates along cleavage planes and the strewing out of the slices along parallel planes. This differential movement or slipping of the mica plates has been frequently observed and described. It is to be noted, however, that this process is not likely to be effective unless the cleavage of the original mica particles is at low angles to the plane of rock cleavage.

The micas which sometimes appear with their dimensional axes parallel to the prevalent cleavage of the rock, but with their mineral cleavage inclined to this plane (figs. 3, 4), may owe their unusual position to granulation or slicing which has not been controlled by the mica cleavage, much as the pyroxenes in the mashed anorthosite, described by Adams,[a] are strewn out by granulation in bands with the pyroxene cleavage at any angle to the rock cleavage. But there is good evidence that associated quartz in bands is itself recrystallized, and it seems probable therefore that recrystallization has affected the mica also.

As we are concerned mainly with parallel structures, it is scarcely necessary to discuss the origin of the random mica particles developed with their own cleavage and longer diameters inclined to the prevalent cleavage of the rock mass (Pl. III). It is easy to prove that such minerals are for the most part porphyritic developments after the rock flowage developing the prevalent cleavage had ceased; the proof is on the same kind of evidence used to prove the later development of garnets, tourmaline, chloritoid, and other minerals of that class.

HORNBLENDE.

It is clear that newly crystallized or recrystallized hornblende particles, which are observed in schists, very greatly preponderate over original particles, and hence that the arrangement is due largely to recrystallization, for the following reasons:

Hornblendic schists are characteristic developments from rocks which have been in the zone of rock flowage under such conditions of great pressure and temperature as to afford favorable conditions for recrystallization.

In many cases the hornblendic schists have resulted from the metamorphism of greenstones or basic igneous and sedimentary rocks in which the hornblende as an original constituent was either wanting or in subordinate quantity. Numberless gradations from such original rocks to typical hornblendic schists have been noted in many regions by many observers.

Where original and recrystallized hornblende occur together in a slide, the new hornblende may sometimes be discriminated by its lighter color or its occurrence as enlargement borders of the original hornblende.

Uniformity of size is characteristic of hornblende particles in cleavable rocks, and this has been shown to be an evidence of recrystallization.

Hornblende particles observed in rocks with secondary cleavage have a greater length relative to breadth or thickness than the hornblendes observed in original igneous rocks, as shown by the measurements given on page 31. In the few specimens measured the average length also was found to be somewhat greater than that of original hornblendes; but many more measurements would be necessary to warrant a positive generalization on this point. The additional relative or absolute

[a] Loc. cit.

length is reached without fracturing, and recrystallization is the only process to which it can be attributed.

Hornblende may frequently be seen to have developed through alteration of feldspar and other material. In the mashed rhyolite-gneiss from Berlin, Wis., it is developed in the tails of the granulated feldspars and does not itself show granulation. In these tails it is parallel to similar hornblende occurring in the groundmass.

White hornblende crystals in cleavable rocks are frequently considerably broken and have many irregularities in arrangement, in general they show a degree of parallelism in their different parts and to the plane of rock cleavage and freedom from strain effects which can not be expected in hornblende crystals owing their parallel arrangement to rotation alone. The natural inference is that both the arrangement and origin of the particles must be due to recrystallization. In a hypothetical case, if a rock in which are numerous slender hornblende crystals with random arrangement be deformed by rock flowage, the hornblende crystals interfere, and, because of unequal transverse support, break or bend at numerous places in order to accommodate themselves to the new conditions. They may become only imperfectly arranged parallel to a plane or line. This interference of the particles in a mass undergoing strain can be shown to be a mathematical necessity. In the rocks with secondary cleavage bending and breaking, due to interference, are subordinate phenomena, and hence it is concluded that crystallization has been important.

From the facts above cited it is concluded that recrystallization of hornblende under pressure has produced the greater part of the hornblende making up the hornblendic schists; hence that recrystallization is mainly responsible for the parallel arrangement, although doubtless it has been assisted somewhat by rotation.

So far as parallel hornblendes now present in rocks with secondary cleavage are original constituents (for the above reasons they are believed to be subordinate in quantity) it must be supposed that they were either in their present position before deformation commenced, or were in a favorable position for rotation to their present position, or are the result of slicing of larger original hornblendes.

Slicing has certainly been instrumental in bringing about the arrangement of many of the hornblendes in hornblendic schists developed from original hornblendic rocks.[a] In a number of rocks have been observed all stages in the process of slicing which has followed the direction of the cleavage of the hornblende (fig. 7). Slices when first formed are likely to be at almost any angle except 90° to the plane of rock cleavage, but it is clear that the majority of them were already at angles less than 45° to the plane of rock cleavage before any rotation occurred.

[a] Sp. 40685, sl. 15360; sp. 40690, sl. 15363, Mesabi district, Minn.

In slides of hornblende-schists there are freqently to be observed random hornblende crystals which lie with their columnar development at high angles to the plane of rock cleavage. These may be original or secondary developments with exceptional arrangement due to local variation in stresses; they may be original crystals which have not been rotated during rock flowage, or they may be secondary developments after deformation has ceased.

QUARTZ.

The quartz particles described under (1) page 31, as having modified crystal outlines and rounded subangular shapes show no direct evidence of granulation or recrystallization or gliding, and in the absence of such evidence, no opinion is offered as to the cause of their parallel arrangement, so far as they have any.

The quartz particles described under (2) pages 31–33, are clearly, both in shape and in arrangement, the result of granulation and slicing, with or without subsequent rotation. Evidence of this has already been presented and will not be repeated.

The quartzes in elongated lenses and spindle-shaped grains described under (3) pages 33–35, may in part develop by granulation or slicing in the manner described under (2) pages 31–33, but most of them, and especially those with more or less even and rounded outlines lacking strain effects, are believed to owe their origin and arrangement, or at least their final configuration, mainly to recrystallization, for the following reasons:

(1) Many rocks with secondary cleavage containing quartz in this form are known to have contained considerable moisture and to have been in the zone of rock flowage under conditions of severe metamorphism favorable to recrystallization. The alteration of muds and sands under such conditions has frequently yielded such forms.

(2) Where the quartz in this form is associated with secondary hornblende or mica in cleavable rocks, as it commonly is, and arranged with its longer diameters parallel to the longer diameters of these minerals, which are characteristic secondary minerals resulting from recrystallization, the presumption is that recrystallizing forces have also affected the quartz. Other common associates of quartz in this form are garnet, staurolite, tourmaline, ottrelite, etc., which are known to be new developments. The manner of association of quartz and mica is also in some cases evidence of recrystallization. The parallel mica plates may be observed to occur strictly parallel to the periphery of flattened quartz individuals, and the ends of the mica plates not infrequently project into clear, limpid quartz which has evidently grown around the mica. (Pl. IX, *A*, *B*.)

(3) In the metaclasic rocks, which have evidently undergone much deformation, the elongated and spindle-shaped quartz forms described

under this head are commonly larger than the quartz grains in undeformed rocks in the same rock mass. Rocks become deformed and cleavable in parts, and such parts may be coarser grained than the remainder of the formation. If an increasing size of grain in a formation is found to correspond with the greater metamorphism occurring at any place, it may be inferred that some constructive process has occurred to increase the size of the grains. Recrystallization is the only constructive process known.

In the Black Hills of South Dakota is a great series of rocks with secondary cleavage which have resulted from the metamorphism of fine-grained banded sediments. The size of the grain in these rocks varies with the amount of metamorphism, and in general not with the original character of the graywacke and slate, although in earlier stages the size of the recrystallized grains corresponds roughly with that of the original grains; it is possible to select a graded series of rocks resulting from the metamorphism of a graywacke slate in which the grain increases as the cleavage and metamorphism are more advanced. This is but one of many illustrations that might be cited.

(4) As important as the size of the grain is the evenness of grain in determining recrystallization. While different degrees of metamorphism are likely to be associated with different sizes of grain, rocks showing the extremes of metamorphism, the best cleavage, and abundant evidence of recrystallization have a curious uniformity of grain in particles of the same mineral species. There are no phenocrysts nor matrices. Quartz in the elongated lenses is seen to share in this uniformity of grain, affording confirmatory evidence that its development in such cases is by recrystallization.

(5) In a rock with secondary cleavage quartz particles are frequently seen to lie in narrow layers of rather uniform thickness composed of numerous narrow individuals lying side by side, as shown in fig. 4 and Pls. VII–X. The individuals are frequently joined by narrow zones of diffuse extinction, due to the inclination of the contact plane. The layers for a considerable distance, while extinguishing in various parts, are still continuous crystalline masses of quartz without mechanical breaks and without other strain effects commensurate with the deformation they must have undergone. It is believed that these features can be explained best by recrystallization. It is perfectly clear that the long band as it now stands could not have been rotated to its present position as a whole. It is possible, and indeed probable, that some of the individual parts represent small quartzes or fracture pieces of quartz which have been rotated into approximate parallelism or carved in situ by granulation or slicing. However, the continuity and evenness of banding can not be explained in any such way. Granulation or slicing could scarcely yield such close fitting parts, and these processes would furthermore result in the development of

minute granules strewn out in the plane of rock cleavage. Even if granulation and slicing could yield elongated individuals so peculiarly fitted together, they would be likely to taper off at the ends and give way to finely granulated material, as in the case of the granulated feldspar figured on p. 37, which shows the best parallel arrangement due entirely to granulation which has been observed in this investigation. The absence of associated granulated material with the quartz bands is evidence that either granulation has never occurred or if it has occurred that recrystallization has coalesced the separate granules; and if this has happened, it is reasonable to assume that recrystallization has also affected the original residual particles.

The narrow quartz bands frequently resemble veins at first glance. If they were veins they would still be the result of crystallization. But close examination shows points in which they differ from veins. The individual quartzes in a vein do not have great elongation in the direction of rock cleavage; they form a mosaic. If a vein, there ought to be found discoloration of some sort due to weathering along the walls of the vein; this is uniformly absent, and even if present, it might still be explained as material pushed aside during the recrystallization of the quartz. No common conditions are known in which numerous veins would develop in this way parallel to the plane of rock cleavage for long distances without breaking across it at places, although this might happen exceptionally in planes of cleavage along which minute jointing had occurred. Neither do veins show the evenness and parallelism shown by these bands. Lastly, the material of these bands in many cases is the only other material present in the rock besides the micas or feldspars. If the quartzes represent veins, we must suppose the rock before the vein action commenced to have been entirely composed of parallel mica plates or layers of feldspar, which is not probable.

(6) In the case of the quartz-porphyry of the Thüringer Wald, so frequently referred to, the shape of the quartzes is again indicative of recrystallization. The long curving tails on these quartzes, which show undulatory extinction and minor fracturing, but still retain their essential unity, could scarcely have resulted from any other process.

(7) Where the quartzes are seen to have cores of older quartz surrounded by rims of new quartz, usually divided by a ring of ferrite or other inclusions, there is conclusive proof of the partial recrystallization or growth of the quartz. The old and the new quartz are in crystallographic continuity. The new quartz, while in optical continuity with the original quartz, is usually added only along directions of easiest relief.

Quartz is sometimes seen completely inclosing other minerals which are original. While this might supposedly happen before the final solidification of the rock from a magma, in rocks with secondary cleavage it probably commonly indicates recrystallization of the quartz subsequent to the original solidification of the rock.

(8) If in a rock which had been clearly subjected to great pressure, as evidenced by the breaking of the feldspars and of some of the quartzes, some of the quartzes are comparatively free from strain effects or fractures, it can be supposed that the quartzes have readjusted themselves to the prevailing conditions by crystallization or recrystallization, thus obliterating their strain effects. Of course, strain effects may still be present and recrystallization have occurred. Indeed, in most cases recrystallization is believed to lag behind deformation to such an extent that some strain effects are visible. The statement should perhaps be that if the quartz shows any less fracturing or strain shadows than other minerals of the rock, this is evidence of the recrystallization of the quartz.

A characteristic strain effect in quartz is the inclusions so frequently observed. These are commonly in planes which in slides appear like lines. They consist largely of cavities containing gas and water and minute mineral particles. Observation shows these planes of inclusions to be closely associated with other pressure effects, such as undulatory extinction and fracturing. There is frequently complete gradation from tenuous and ill-defined planes of inclusion to well-marked planes and fractures.[a]

Further, these inclusions may be in planes intersecting one another at high angles, frequently at an inclination of 45° to the plane of greatest diameters of the quartz or to the plane of rock cleavage. According to principles given, pp. 121–124, they may be phenomena of fracture in shearing planes. In a quartz in which there has been no strain it is believed that these planes of inclusions are less numerous and have less regularity of arrangement; but this is hard to prove, as it is so extremely difficult to find a rock containing quartz which can be proved not to have undergone strain.

When tested by the above criteria the shape and arrangement of the elongated quartz bands or elongated spindle-shaped quartz masses (3), seem probably to have resulted mainly from recrystallization. Yet there may have been also subordinate gliding, granulation, and rotation, for recrystallization obliterates evidences of these processes.

When the quartz grains are nearly equidimensional, or the grain is finer, the above criteria are less effective. Many quartz crystals which are nearly round and show no evidence of recrystallization by any of the above criteria, have undoubtedly been recrystallized. Where the grain is exceedingly fine it is impossible to apply these criteria, and one is unable to tell by direct observation what processes

[a] See figs. 3 and 4 of Van Hise's paper on the pre-Cambrian Rocks of the Black Hills: Bull. Geol. Soc. America, vol. 1, 1890, pp. 216, 217.

or what combination of processes have been effective in producing the fine-grained groundmass of many cleavable rocks.

Quartz crystals have been made to glide under pressure experimentally, but it is certain that little or no evidence of such gliding is now to be observed in the quartz of the cleavable rocks. If gliding has occurred, evidence of it has been obliterated by recrystallization and granulation. The only strains in quartzes now to be observed that are of the same order as those of gliding are those of undulatory extinction, and the comparative absence of this phenomenon, as seen above, is regarded as evidence that recrystallization has occurred.

In general the quartz particles showing evidence of recrystallization in cleavable rocks are not so numerous as those lacking such evidence, but if this statement is confined to quartz particles showing parallel arrangement, the evidence of recrystallization preponderates over that of any other processes causing such a parallel arrangement. Recrystallized quartz particles are certainly less abundant than recrystallized mica or hornblende, and probably more abundant than recrystallized feldspar. Evidence of granulation and rotation is more abundant in quartz particles than in mica or in hornblende particles, and probably less abundant than in feldspar particles, but these processes have yielded but a poor arrangement. So far as recrystallization works upon granulated and rotated particles it tends to obliterate evidence of granulation and rotation, and hence the evidence now observable may not in all cases measure the extent to which granulation and rotation has actually occurred.

FELDSPAR.

In the presentation of the facts of arrangement of the feldspars the feldspar particles were classified according to shape.

The feldspars occurring with more or less modified crystal outlines and random arrangement described under (1) on page 35 may be either original or recrystallized. From their shape they could not have been granulated. The crystals described under (1a), which have random arrangement and around which the other constituents of the rock bend, are original as compared with other constituents, for they have evidently acted as rigid units during the deformation of the rock, the other constituents being crowded about them and thus frequently showing strain effects. If recrystallized, they would be likely to have a parallel arrangement or to include the other constituents, as in the case described below.

The crystals with random arrangement described under (1a) as not crowding the other constituents of the rock but containing them in lines parallel to the plane of rock cleavage must be recrystallized, for the minerals contained are quartz and mica in parallel bands which themselves can be proved to be recrystallized. The development of the feldspars must have been subsequent to the recrystallization of the quartz and mica. If original in their present form and arrangement the crowding must inevitably have occurred during the development of the parallel arrangement in the other constituents of the rock. Furthermore, they lack strain effects which they must have shown if they were there during the deformation of the rock. Their large size as compared with that of other constituents results from the fact that their development by recrystallization occurred after the rock deformation ceased, when granulation no longer breaks down the grains as fast as recrystallization builds them up.

Crystals with more or less modified crystal form occurring in dimensional parallelism to the plane of rock cleavage (1 b, pp. 35–37) owe their shape and probably their parallel arrangement to recrystallization. That recrystallization is responsible for their development is proved by the evidence cited above, that is, the presence of recrystallized quartz and mica through the feldspars without change of direction and further by the lack of strain effects commensurate with the deformation which the rock has evidently undergone. In some cases, also[a] such crystals have been observed to be the alteration products, with mica and garnet, of a larger feldspar crystal. The association with other recrystallized minerals such as hornblende, is further presumptive evidence of recrystallization. Rarely the feldspar crystals under this head have received their arrangement through slicing along feldspar cleavage planes and rotation.[b]

The angular particles described under (2) on pages 37–39 might be either in original form, granulated, or recrystallized, but their shape is probably in most cases, if not in all, either original (i. e., the same as in the undeformed rock from which the cleavable rock is derived) or due to granulation. If recrystallization has affected them it has left them with a shape quite different from that characteristic of recrystallized particles described above and below. All stages of granulation from the original mineral to the finely granulated particles may actually be seen in many slides. Where such gradations are absent the angular form is itself presumptive evidence that the form is due either to granulation or original character. Evidence of the rotation of such granulated particles toward the common plane of cleavage is almost uniformly present. In certain cases, as in the anorthosite described by Adams (pp. 37–38 and figs. 13 and 14) the elongated forms are clearly the result of granulation or slicing along the peripheries, leaving residual parallel grains. In many other cases the evidence for recrystallization or granulation is not decisive.

The lenticular and ribbon forms of feldspar described under (3) on page 39 are in part, both in shape and arrangement, the result of

[a] Sp. 6021 W., Wausau, Wis.

[b] Sp. 6021 W. in part, Wausau, Wis.

recrystallization. The criteria for determining this are identical with those used in determining the origin and processes of arrangement of similar bands of quartz (pp. 82–86).

In general the feldspars, which clearly owe their shape and parallel arrangement to recrystallization, are relatively rare as compared with particles lacking such evidence and probably arranged largely by rotation and granulation or as compared with still more abundant particles lacking the parallel arrangement. Feldspars without parallel arrangement, but showing evidence of recrystallization, are often observed. Cores and enlargements and new growths along cracks are not uncommon phenomena, but such recrystallization has not yielded a parallel structure and thus does not properly come within the limits of this discussion. Many feldspars show evidence that some combination of these processes of arrangement has been effective, but usually the one or the other is preponderant.

Gliding is not observed to be important. While secondary twinning as an initial stage in granulation is a common phenomenon, in no case has this twinning been observed to have caused any appreciable flattening of the mineral. Where any such possible flattening is present with the twinning, evidence of granulation, rotation, or recrystallization is commonly more conspicuous.

In an exceedingly fine-grained groundmass it is practically impossible to determine, from any phenomena shown by the particles themselves, what processes have been effective, though it may be possible to determine their probable origin by ascertaining the dominant processes which have affected the coarser constituents of the rock.[a]

CALCITE.

In explaining the parallel arrangement of calcite grains several processes may be considered, the common ones—recrystallization, granulation, and rotation—and gliding. Any or all of these processes may be effective in given cases, and it is extremely difficult to determine criteria by which to separate them. Granulation and accompanying rotation are mainly responsible for the shape and arrangement of the angular fragments described on page 41. This is evidenced mainly by the shape of the fragments and their gradation to unbroken crystals. The process determining the shape and arrangement of the small ellipsoidal particles (described on p. 41) is not so clear, but it is thought to be mainly recrystallization, because of the general evenness of texture of the grains, their ellipsoidal outlines, and their comparative freedom from strain effects. Yet it is apparent that granulation may have aided recrystallization and that its characteristic evidences may have become obliterated by recrystallization.

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[a] Sp. 14929, sl. 9460, Black Hills, South Dakota.

Gliding may have been partly effective in any of the above cases. In experiments on the deformation of marble under pressures, Adams has shown that deformation of the calcite crystals may occur by gliding along twinning planes of the crystal $-\frac{1}{2}$ R. This results in dimensional parallelism of the crystals and not in crystallographic parallelism, for gliding may occur, no matter what the original arrangement of the calcite is, and no amount of the gliding will make parallel the relative crystallographic directions of different crystals. The main criterion by which gliding is determined is the increased amount of twinning to be observed. Where the movement occurred by gliding, the crystals were found to be finely striated by polysynthetic twinning grading into minute fractures, giving a reedy or fibrous appearance (Pl. XV). In the calcite particles occurring in cleavable rocks more or less of such twinning is to be observed, and the presumption is that at least some of it is a secondary phenomenon due to pressure and is accompanied by a change in form. But the difficulty lies in ascertaining how much of the twinning is original and how much is secondary, and thus in determining the amount of the deformation brought about in this way. In the particular slides examined, in but few cases did the twinning lines seem to be much more numerous than that common for an unmashed marble. If gliding had occurred extensively, subsequent recrystallization may have obliterated it. In connection with his description of his experiments on the flowage of marble, Adams publishes descriptions of 42 cleavable marbles for comparison. He concludes that while recrystallization undoubtedly plays an important and in many cases probably a chief part in the deformation of marble, the processes of gliding and granulation are also effective.[a]

The facts observed in this study seem to indicate that recrystallization and granulation are by far the most common of the processes producing the arrangement of calcite grains in cleavable rocks. The ease of recrystallization of calcite has been commonly recognized. It is beautifully illustrated under conditions of low pressure by the cementation of marl and by the common change of limestone to marble.

The process of gliding has probably assisted both of the above processes, though in the particular rocks examined in this study the evidence of such assistance has been slight. In the observations of cleavable marbles made by Adams more evidence of gliding was found, and in his experimental work the process has been demonstrated to occur.

If the parallel arrangement of the calcite crystals of schistose marbles is often clearly the result of recrystallization, and calcite is

[a] Adams, F. D., and Nicolson, J. T., An experimental investigation into the flow of marble: Philos. Trans. Royal Soc. London, vol. 195, 1901.

known for other reasons to recrystallize very easily, the question naturally arises why parallel structures in marbles are not more general, for it is exceedingly rare to find marbles with a parallel structure. Crystalline granular marbles without parallel structure frequently appear between very schistose gneisses. In the exceptional cases where parallel arrangement is attained the conditions must be somewhat unusual. Following Van Hise,[a] it may be suggested that the ready recrystallization of calcite and its consequent tendency to develop large individuals by the merging of smaller ones may soon obliterate evidence of parallel arrangement after rock flowage has ceased, and that a parallel arrangement appears only when the rock flowage and development of a parallel structure has occurred so recently that subsequent recrystallization has not had time or the proper conditions to obliterate the parallel structure. In other words, the parallel structure developed by granulation or recrystallization under dynamic conditions may be obliterated by subsequent recrystallization under static conditions.

CHLORITE.

No presentation of evidence is necessary to show that chlorite in parallel flakes in cleavable rocks is a development by crystallization or recrystallization. The development of chlorite from other minerals has been so frequently observed and described that its secondary nature is accepted as a matter of course.

In many schists chlorite is partially or wholly pseudomorphous after the micas, in which case its parallel arrangement is that of the mica. In other cases chlorite is a development from minerals of appropriate composition which originally had no parallel arrangement. In either case the shape and arrangement are due to recrystallization.

TREMOLITE, ACTINOLITE, GRÜNERITE, AND OTHER AMPHIBOLES.

These minerals are in all cases certainly the result of crystallization in metaclasic rocks, as may be proved by field occurrence, where their development may be traced from rocks originally having none of these minerals. Their arrangement in certain cases in the plane of rock cleavage may be explained (1) by recrystallization during rock flowage; (2) by recrystallization after movement ceased, the plane of rock cleavage affording directions of easiest development of the crystals; (3) by rotation of recrystallizing and recrystallized particles. What combination of these factors in a given case has been effective in producing the very partial arrangement observed in these minerals is difficult to determine. If (1) were effective we should expect to find

[a] Van Hise, C. R., A treatise on metamorphism: Mon. U. S. Geol. Survey, vol. 47, 1904, pp. 754–755.

a better arrangement than we do find. If (3) were effective we should expect to find considerable breaking and interference of the fibers. Explanation (2) seems to afford the best explanation of the facts observed and this is accordingly given emphasis, although it is not meant to imply that the two others may not have been effective to a subordinate degree.

GARNET, STAUROLITE, TOURMALINE, ANDALUSITE, CHLORITOID, ETC.

Garnet, staurolite, tourmaline, andalusite, chloritoid, and the other crystals of this class in cleavable rocks are uniformly porphyritic. Their development in such rocks is largely by recrystallization, which occurs after rock flowage has ceased and is favored by high pressure and temperature, as is evidenced by their high specific gravity and characteristic association with great masses of intrusive igneous rocks. Evidence of their development by the recrystallization of the rock mass and recrystallization later than the rock flowage that has produced cleavage is shown by the following facts: (1) They appear in rocks clearly derived by rock flowage from rocks originally lacking such minerals. (2) They frequently lie at high angles to the prevailing cleavage in the rock. (3) They do not show the degree of mechanical deformation that they would necessarily show had they developed in their present positions before rock flowage had ceased. Many of the crystals are long and acicular, and would surely have been broken if any considerable movement had occurred subsequent to the development. (4) They include, within their outlines, minerals in part similar to those in the remainder of the rock with an arrangement of their greater diameters in the plane of rock cleavage (Pl. XIII), an arrangement in part at least developed during rock flowage. (5) The mica and the other constituents of cleavable rocks, which are certainly developed by recrystallization during the process of deformation, are frequently seen to end abruptly at the periphery of the minerals of this group and to pass them by without any change of direction or crowding. If rock flowage under which the micas developed had occurred subsequent to the formation of the porphyritic crystals, crowding and bending of the micas must inevitably have occurred and would doubtless not be obscured by their subseqent recrystallization. (6) The usual large size of minerals of this group, as compared with their associated mineral particles, is due to their development subsequent to rock flowage, when granulation is no longer acting to break down the crystals.

While the development of this group of crystals is believed to have been mainly subsequent to the development of the rock cleavage, it is true also that in some cases further flowage occurred subsequent to their development, as shown by fracturing of the crystals and the crowding of the other constituents. The very fact that the effects of further movement are so conspicuous confirms the conclusion that the crystals not showing these effects developed after the movement ceased.

SECTION III. GENERAL PREDOMINANCE OF PROCESS OF RECRYSTALLIZATION.

By comparing the discussion of the cleavage-producing capacity of mica, hornblende, quartz, and feldspar which make up the great bulk of the rocks with secondary cleavage, with the discussion of the processes which have determined their shape and arrangement, it appears that the mineral grains yielding the best flow cleavage are the ones which are described as showing conspicuous evidence that their shape is due to recrystallization, and if our idea of the factors and conditions controlling recrystallization is correct, the arrangement of such recrystallized particles is also due largely to the same process. It is an observed fact that in general, so far as evidence of recrystallization is absent, the parallel arrangement also is lacking. (The reverse proposition does not hold.) Yet there is evidence, also, that granulation and slicing occasionally develop an excellent parallelism and may have been effective also in producing the parallel arrangement of particles which clearly bear the stamp of recrystallization as the last and dominant process. Evidence of rotation of original and granulated particles unaccompanied by recrystallization is conspicuous only in certain original and granulated mineral particles which are not so well adapted to give a good rock cleavage as the particles in which evidence of recrystallization is apparent. It is certain, however, that rotation has accompanied recrystallization in many grains which now show evidence only of recrystallization, for during the rock flowage which developed the cleavage rotatory stresses must have been generally active, as will be shown on a subsequent page (pp. 109–118). There is practically no evidence of gliding in these principal cleavage-giving minerals.

The relative importance of the various processes giving the parallel arrangement to the remaining minerals of metaclasic rocks is a matter of little consequence for the reason that such minerals have for metaclasic rocks as a whole so little effect on rock cleavage. In calcite all processes, recrystallization, granulation, gliding, and rotation are effective; the order given is probably also the order of their importance. Calcite is the mineral best adapted to change its form by gliding, and is the only one in which this process has yet been shown to be effective, but even here this process is probably subordinate to recrystallization. From evidence to be observed in the rocks themselves, gliding is therefore practically negligible. In the remainder of this group of minerals the origin is almost entirely recrystallization, and the arrangement, so far as there is arrangement, is doubtless due mainly to the same cause, although rotation may have had some effect.

Investigations have shown in certain instances that the cleavability of a rock varies with its composition.[a] This expresses also the fact that cleavability varies with mineralogical composition. In the development of flow cleavage in a noncleavable rock there is both chemical and mineralogical change and redistribution of substances. This occurs through recrystallization. Hence the close relation not only between cleavability and composition, but between these two and recrystallization.

SECTION IV. ORDER OF RECRYSTALLIZATION.

It has been seen that certain minerals develop secondarily in cleavable rocks by recrystallization more readily than others. It is not possible to make definite statements concerning the order of facility of crystallization or recrystallization of different minerals, because of the fact that certain of the cleavage-making minerals, such as hornblende, usually develop to the exclusion of others, such as micas; the cleavage rocks in which hornblende and biotite or hornblende and muscovite occur together are very few. We know definitely that quartz generally recrystallizes before feldspar, and mica and hornblende before quartz and feldspar. In a few cases[b] we know also that the biotites have developed before the hornblendes, but how generally this statement can be made to apply is a matter of doubt. As to the micas, it is certain that the muscovite and biotite, when they occur together, usually develop simultaneously; they are interleaved in a most intricate fashion, and the development of one or the other is apparently a matter of the substances available. Exceptionally the muscovite evidently crystallizes before the biotite. The recrystallization of calcite has not been compared directly in the same slide with the development of the minerals above named, but it is known that this mineral recrystallizes very easily and probably relatively early in rock flowage. Chlorite perhaps in some cases develops simultaneously with the micas, but it is certain that in other cases it develops later as an alteration of micas or other minerals. Where it is developed to the exclusion of the micas it is of course difficult to compare its ease of recrystallization with that of the micas. Actinolite, grünerite, and tremolite are certainly in many if not in most cases crystallized out later than the principal cleavage-making minerals, as is evidenced by their unbroken form and random arrangement in rocks which show parallel arrange-

[a] See articles by Reade and Holland in Proc. Liverpool Geol. Soc. for 1899-1900, pp. 463-478, and for 1900-1901, pp. 101-127. See also Harker, Rept. 55th Meeting Brit. Assoc. Adv. Sci., 1885, p. 828.

[b] Sp. 18037, sl. 9589, near Hudson River, New York.

ment by crystallization or recrystallization of other constituents. The same statement may be made with reference to the group of heavy minerals, such as garnet, staurolite, andalusite, chloritoid, tourmaline, etc. They are all developments by crystallization very late in the process of deformation or after deformation has entirely ceased. Their development is also later than the recrystallization of calcite or chlorite and, in most cases at least, of actinolite, grünerite, and tremolite.[a]

It is interesting to ascertain whether or not the order of recrystallization or crystallization of the various minerals of cleavable rocks bears any uniform relation to any of their mineral properties, and to attempt to ascertain what properties have caused the minerals to recrystallize in this order during rock flowage. So far as one can judge from the above facts, there is no obvious arrangement of the mineral properties corresponding with the order of recrystallization. The specific gravity in the four principal schist-making minerals—mica, hornblende, quartz, and feldspar—ranges roughly from higher in the easiest and first recrystallized to lower in the last recrystallized. In chemical composition there is apparently no order. The symmetry shows no regular variation. The mineral habit varies from greater inequality of the dimensional axes to less inequality. In the less important minerals which undoubtedly crystallize later in rock flowage, there is the same irregularity and uncertainty in the order of properties. Instead of having a lower specific gravity than the principal cleavage-giving minerals above named, these minerals have a higher one. In symmetry and shape they show greater variety; in some instances the crystals have less inequality of dimensional axes than the principal cleavage-making minerals and in other cases more.

The conditions determining the order of development of the various cleavage-making minerals by crystallization or recrystallization during rock flowage are evidently somewhat complex, and not evidenced by a simple graded series of mineral properties. The form and kind of mineral developing at any stage in the process may be conditioned by factors of temperature and pressure, substances available, crystal shape and symmetry of the particles which may develop at that point, their specific gravity, etc. For different minerals and conditions different factors are dominant, and a comprehensive discussion of the causes of the order of development during rock flowage would involve a detailed description of many factors affecting each mineral, which would make a paper in itself. Van Hise[b] has made an exhaustive study of these factors, and the reader is referred to his work on metamorphism. One principle, however, may be empha-

[a] See slides and specimens from Republic Mountain and Humboldt Mountain, Marquette district, Michigan.

[b] Van Hise, C. R., Mon. U. S. Geol. Survey, vol. 47, 1904.

sized. While the minerals developing at any place or time during rock flowage are limited in their variety by the substances available in the capillary and subcapillary solutions, it may be supposed that if at any point such substances are present that any one of several minerals might develop, the mineral best adapted by its high specific gravity and especially shape, as shown by the above facts, to the conditions of pressure there existing will be the first one to form, although other factors may have a modifying effect. It is an observed fact that minerals developed by recrystallization during rock flowage have as a rule higher specific gravities than the minerals originally present in the rock or minerals developed under conditions of weathering, and thus the development of a rock with a good cleavage through recrystallization means a diminution of volume. It is further a matter of observation, as shown in the foregoing pages, that the minerals showing the best evidence of recrystallization are the ones which by their shape and dimensions are best adapted to the conditions of unequal pressure which have existed during the deformation of the rock.

CHAPTER IV.

MISCELLANEOUS OBSERVATIONS ON THE INTERNAL STRUCTURE OF CLEAVABLE ROCKS.

SECTION I. WHY SOME MINERALS SHOW CRYSTALLOGRAPHIC PARALLELISM AND OTHERS DO NOT.

It has been shown that minerals of different kinds in metaclasic rocks do not exhibit a parallelism of their crystallographic or vector properties, but that particles of the same mineral species do show such parallelism in so far as these properties have uniform relations to the dimensions of the particles. In other words, the minerals are always controlled in their arrangement by their dimensions, and in so far as the vector properties happen to be in uniform positions with reference to such dimensions these properties are themselves parallel. The parallel crystallographic arrangement of particles of the same mineral is thus a phenomenon subordinate to, and dependent upon, the dimensional arrangement of the particles. This uniform relation of the crystallographic properties to dimensions and consequently the parallel arrangement of the crystallographic properties are found in cleavable rocks only in the particles of minerals which have a strong tendency to occur with strongly marked crystal habit, such as mica and hornblende. In developing by recrystallization during rock cleavage, as these minerals do for the most part in cleavable rocks, their tendency to take on definite crystal forms, working under the general law of dimensional control, requires that the crystallographic axes of the particle shall also be arranged in parallel positions. Minerals such as quartz, feldspar, and calcite, which lack a strongly marked crystal habit or cleavage form in metaclasic rocks, commonly do not show a parallelism of the crystallographic properties of the different particles. It is known that the tendency to the development of quartz and calcite in columnar forms is slight. Any small accident of crystallization may cause the development of short, stumpy crystals whose length is not greatly different from their thickness. This is shown in quartz by a tendency to develop terminal faces, manifesting itself in striations on the pyramidal faces, in this contrasting strongly with hornblende, which has a strong tendency to columnar habit without the development of terminal faces. For this reason in meeting the requirements of dimensional arrangement under rock flowage, quartz, and calcite in recrystallizing do not necessarily arrange their crystallographic axes. The tendency toward developing in characteristic crystal shape is not strong enough to orient the crystallographic properties when the mineral is arranging itself dimensionally under pressure. The same statements apply in a less degree to feldspar.

Under exceptionally favorable circumstances it would be natural to expect that the tendency, slight though it is, for quartz, feldspar, and calcite to take on characteristic crystal shape with characteristic dimensions, would cause the crystallographic properties to be parallel, and this, except for calcite, seems to be the case in exceptional instances, as shown in Chapter II.

The reverse proposition, that all minerals showing strongly marked crystal habit in cleavable rocks have also crystallographic parallelism, does not hold, for the fact has repeatedly been emphasized that many minerals, such as tourmaline, chloritoid, etc., and exceptionally even feldspar and biotite, develop late in the process of rock flowage or after rock flowage has entirely ceased, and usually lack not only crystallographic but even dimensional parallelism.

SECTION II. MOLECULAR SHAPE AND RECRYSTALLIZATION.

There is a significance in the entirely new development by recrystallization of minerals, such as mica and hornblende, with strongly marked crystal habits and with parallel dimensional and crystallographic arrangements. The outward form of a crystal is commonly taken to be a manifestation of its internal structure. The characteristic dimensions of a crystal may be supposed to be conditioned by the molecules themselves, because of their shape or manner of aggregation or both. It may be supposed further, then, that the dimensional control of the arrangement observed in the crystals developed entirely by recrystallization in metaclasic rocks will apply equally well to the very first molecule or group of molecules of these minerals which began to develop; in other words, that the very first molecule or group of molecules which were brought together by crystallization or recrystallization to make up the crystals of these minerals were controlled in their initial position by the conditions of unequal pressure existing during the rock flowage. They were actually squeezed or held in parallelism by the differential pressure. Whatever molecular property gives the characteristic shape to crystals causes the arrangement of the molecules under pressure. So far as fortunately oriented crystals survive or continue to grow, it may be that the molecular properties determining their shape meet the requirements of dimensional control. In discussions of the molecular structure of a mineral, it has ordinarily been assumed that the shape of crystals is due to molecular grouping, i. e., the molecules have been considered as essentially equidimensional bodies, and the differences in symmetry and shape of crystals have been considered to depend upon the spacing of the molecules. One would expect, therefore, that, as the first molecules of the newly developing crystal aggregated themselves in a rock undergoing flowage, their tendency to unequal spacing in different crystallographic directions would give the crystal at once unequal dimensions. This would cause its orientation with its shorter diameters parallel to the shortening of the rock mass, and in mineral particles so arranged the greater molecular spacing would be looked for in the direction of the greatest dimensional axes of the crystals—that is, normal to the shortening of the rock mass. But it has further been held by crystallographers that mineral cleavage is dependent upon the spacing of molecules, the molecules being spaced more closely in the planes of mineral cleavage than transverse to them. On such a hypothesis it must be assumed that in developing by recrystallization during rock flowage, the micas, for instance, take a position with the greater spacing of the molecules parallel to the shortening of the rock mass, a direction in which one would expect the molecules to be most closely spaced. If the molecules were most widely spaced in the direction of the least dimensional diameter of the mica, as required by the theory of mineral cleavage, it is difficult to understand how the minute beginnings of mica crystals, or the first aggregates of molecules which can be called crystals, could arrange themselves, as they unquestionably have, under the law of dimensional arrangement. Such considerations, together with the complete dimensional control of the arrangement of newly developing mineral particles in a rock undergoing rock flowage and the complete dependence of rock cleavage upon the parallel arrangement of unequidimensional mineral particles, suggest that possibly the more minute constituents or structural elements of these crystallographically parallel mineral particles may be arranged under similar laws; the molecules themselves may have unequal dimensions and be arranged under the law of dimensional control shown by the crystal particles. It would follow that minerals dimensionally and not crystallographically arranged, such as most quartz, calcite, and feldspar particles, have molecular shapes such that in the beginning of their development they may meet the requirements of dimensional control without necessarily arranging their crystallographic axes.

As another possibility the molecules might be both dimensionally arranged and unevenly spaced, giving several possible combinations of arrangements. It might well be that with the parallel dimensional arrangement of the molecules there is a wider spacing in directions normal to the greater diameters of the molecules. This would allow newly developing mica particles to meet the requirements of dimensional control and at the same time to arrange their mineral cleavage, assuming this to be conditioned by the wider spacing of the molecules in planes normal to the shortest dimensional diameter.

An interesting and perhaps significant fact in this connection is the common position of the optic axis $\mathfrak{a}$ normal to the greater dimensions in such minerals as the micas. This means that the rays propagated normal to the plane of cleavage and vibrating parallel to it travel more rapidly than others. The behavior of light in such crystals may be influenced by the possible dimensional arrangement of the mineral molecules here suggested. However, a discussion of the possible nature of such influence must include so many factors, many of them of yet doubtful nature, that it must be left to some other time and place.

SECTION III. FLOW CLEAVAGE AS A MOLECULAR PHENOMENON

It is clear that as flow cleavage is a capacity to part, not an actual parting, whether along mineral cleavages or between mineral particles due to their weak adhesion, it is a molecular phenomenon. Parting can occur only by breaking certain bonds of molecular attraction. It is necessary only that the bonds of molecular attraction should be less strong along certain parallel lines or planes than along others. A definition of flow cleavage, in terms of molecular attraction, would thus read as follows: Flow cleavage is a capacity to part along parallel planes or lines or surfaces, due to weaker molecular attraction along such parallel planes or lines than in other directions in the rock. This allows of parting parallel to a number of sets of lines or planes, but where one set gives an easier parting than another only the easier one is likely to appear.

When a rock with flow cleavage is cleaved, it is observed that the parting occurs either between separate mineral particles, which act as units during parting, or along cleavage planes in the mineral particles themselves or commonly both. Where the mineral particles act as units, the parting has been observed to occur most readily along planes or lines in which the fewest mineral particles are to be met with. In the common cases this is obviously in the plane of the greatest and mean diameters, or in any planes or surfaces parallel to the greatest diameter of the mineral particles. The parting occurs less readily in the plane of the greatest and least axes, and still less readily, or not at all, in the plane of the least and mean axes of the particles. Where the particles act as units in the parting, the adhesion of the particles to one another is weaker than the internal cohesion of the individual particles. The planes of parting are separate entities; they are finite in number, and have definite positions in the rock. For convenience in discussing flow cleavage, the parting so occurring between the mineral particles rather than through them may be called intermineral or adhesive cleavage. Such cleavage is likely to yield few possible planes of parting visible in the hand specimen. Where during the parting of a metaclasic rock the particles do not act as units, but break along their own parallel mineral cleavages, the number of possible planes of parting through the minerals so arranged may be almost infinite in number. The cohesion of the substances of the particles is less than the adhesion of the particles to one another. Cleavage so produced may be called cohesion cleavage, to distinguish it from the intermineral or adhesion cleavage. Because of its fineness it might perhaps be distinguished as microcleavage. As already intimated adhesion and cohesion cleavage commonly occur together in rocks.

All flow cleavage belongs under one or both of these heads. The terms are superfluous for ordinary descriptive purposes, but are convenient in a discussion of this phase of the subject.

The preceding discussion of the effect of the individual minerals on the production of cleavage has given data for a general statement of the relative importance of intermineral and cohesion cleavage in metaclasic rocks as a whole.

Cohesion cleavage seems to be important so far as mica and hornblende are present in a metaclasic rock, and adhesion cleavage so far as quartz and feldspar are present. The presence of mineral cleavage faces in the rock cleavage partings is evidence of the cohesion cleavage, while their absence is taken as evidence of adhesion cleavage. But, while the presence of mineral cleavage faces on the rock cleavage parting surface is necessary when the rock is parted along cohesion cleavage planes, it does not follow that the presence of such mineral cleavage planes always indicates that the rock cleavage was of the cohesion variety alone, for the shapes of hornblende and mica particles in cleavable rocks are determined by mineral cleavage, and it is very difficult to tell on the rock cleavage surface whether the mica and hornblende there appearing have been parted along their own cleavages or are in their original forms. While adhesion cleavage can occur alone, cohesion cleavage is rarely, if ever, present to the exclusion of the adhesion cleavage. It is to be remembered that the micas and hornblendes never make up the entire mass of a rock, but are usually separated by layers of quartz or feldspar, or both, and even if these minerals were not present the cleavage would not be cohesion cleavage alone, but partly adhesion cleavage between different mica or hornblende individuals.

It can be said, then, that so far as quartz and feldspar appear on the cleaved surface of a metaclasic rock, as it does in many quartz-feldspar gneisses, the rock cleavage has probably been mainly of the adhesion variety. So far as mica and hornblende appear, the rock cleavage probably has been both of the adhesion and cohesion varieties. While adhesion cleavage is nearly always present, the fact that cohesion cleavage is certainly important for the micas and hornblendes indicates that cohesion cleavage in cleavable rocks may be as important if not more important on the whole than adhesion cleavage.

So far as chlorite is present in the rock the cohesion cleavage is dominant. So far as actinolite, grünerite, tremolite, staurolite, tourmaline, and chiastolite are present, and have parallel arrangement, probably the adhesion cleavage is important.

Calcite in finely fissile limestones or marbles yields an adhesion cleavage alone, as is evidenced by the characteristic absence of calcite cleavage on cleavage surfaces of such rocks and by the absence of parallelism of the calcite cleavage as observed microscopically.

CHAPTER V.

OBSERVED RELATION OF FLOW CLEAVAGE TO THE ELONGATION AND SHORTENING OF ROCK MASSES.

If the relation of flow cleavage to the elongation and shortening of rock masses is certainly known, its relations to pressure may be worked out. The relation of flow cleavage to elongation and shortening of a deformed rock mass may be shown by (1) the distortion of pebbles of a conglomerate, (2) the distortion of mineral crystals, (3) the distortion of volcanic textures, (4) the distortion of fossils, (5) the distortion of beds and attitude of folds, (6) relations of cleavage to intrusives, (7) the position of fractures. It is scarcely necessary to attempt an exhaustive discussion of each of these lines of evidence, they are so common and well known. But of each a few illustrations to show the nature of the evidence may be given.

(1) *Distortion of pebbles of a conglomerate.*—Schistose conglomerates show by the distortion of their pebbles, either with or without fracture, the directions of elongation and shortening, although it may sometimes be difficult to distinguish the shapes of undeformed pebbles from those of deformed pebbles. As illustrative examples may be cited: Conglomerates from the iron districts of the Lake Superior region[a] (See Pl. XXVII), from Crystal Lake in California, from the Black Hills of South Dakota,[b] from Madoc, Ontario,[c] from the Green Mountains of Vermont, and from the Front Range of Colorado. Sederholm[d] describes squeezed conglomerates from Finland, Harker[e] cites a number of instances in his discussion of rock cleavage, and Lehmann[f] figures several in his crystalline schist report. Instances could be cited from almost every known area of pre-Cambrian sedimentary rocks.

In all of these conglomerates the matrix is schistose or cleavable, and the schistosity or cleavage is approximately parallel to the greater

[a] Sp. 25718, north of Felch Mountains, Michigan; sp. 42094, fracture in pebble, north shore of Lake Superior; sp. 45810, Pine River, Wisconsin.

[b] Sp. 14818, Black Hills, South Dakota.

[c] Sp. 18391 and 18392, Madoc, Ontario.

[d] Sederholm, J. J., Archean sedimentary formations: Bull. Geol. Survey of Finland, No. VI.

[e] Harker, Alfred, Rept. 55th Meeting Brit. Assoc. Adv. Sci., held 1885, published in 1886, p. 837.

[f] Lehmann, Origin of the Crystalline Schists; Atlas, Pl. VII, figs. 5 and 6; Pl. XVII, fig. 4.

diameters of the flattened pebbles, although bending at the ends of the pebbles in following their peripheries. Where the flattening of the pebbles has been extreme, as in a specimen illustrated in Pl. XXVI, *A*, *B*, the longer diameters of the pebbles not only coincide with the cleavage of the rock, but at the squeezed end of the specimen the outlines of the pebbles may not be distinguished.

In some instances also, and probably in many, the flattening of the pebbles has resulted in developing a cleavage within them, and this cleavage has been observed to be parallel to the flatness of the pebbles. In a schistose quartzite conglomerate[a] from the Metropolitan district, Michigan (fig. 27), and in a schistose breccia-conglomerate from Madoc, Ontario, sections through the pebbles show that the individual quartzes making up the complex pebbles have been uniformly elongated by recrystallization in the same plane in which the pebble as a whole has been elongated. In the same rocks, also, there is evidence of slicing and granulation of certain particles in the pebbles, resulting in a parallel arrangement slightly inclined to the plane of elongation of the pebbles. Parallelism of constituent minerals is excellently developed in much elongated slate, schist, and diorite pebbles in a slate conglomerate from Pine River, Wisconsin (Pl. XXVII, *A*, *B*, *C*). While in a few cases the parallel arrangement of the mineral constituents may have existed in the pebble before it became a part of the conglomerate, there is no question that the prevailing parallel structure has been developed by the secondary deformation which has affected the rock as a whole. In these cases, and in others, the cleavage of the pebbles may be good or poor, depending on the nature of the constituents, and on the extent to which the matrix has taken up the deformation, but, such as it is, the cleavage is parallel to the longer diameters of the minute particles making up the pebbles, to the plane of elongation of the pebbles as a whole, and finally to the schistosity or cleavage of the rock mass as a whole.

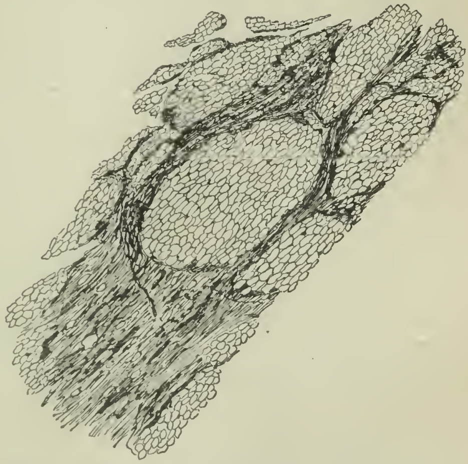

FIG. 27.—Pebbles of quartzite with constituent quartz grains elongated by recrystallization in the plane of elongation of the pebbles and of the rock as a whole. Schistose conglomerate from Metropolitan, Mich. Large slide.

[a] Van Hise, C. R., Principles of pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, Pl. CXV.

Illustrations might be multiplied, but the cases here cited will serve to show the bearing of this line of evidence on the subject in question.

(2) *The distortion of mineral crystals.*—The distortion of crystals, either by recrystallization or by granulation, is a commonly observed phenomenon. In the description of the features of occurrence in the rocks with flow cleavage in Chapter II instances of this are cited. Numerous slides have been observed in which the plane of cleavage is marked by mica plates or hornblende crystals, while the associated quartz and feldspars show fractures at angles with the plane of cleavage (figs. 9, 16, 17). Where, accompanying these fractures, there has been displacement of the parts, as is frequently the case, this displacement is observed to work toward extending the fractured particle in the plane of rock cleavage and shortening it normal to the plane of cleavage. Lehmann figures a number of instances of this.[a] Van Hise[b] quotes Keith as making the following statement:

> Near Blowing Rock, N. C., is a mashed porphyritic granite in which porphyritic crystals of feldspar are flattened in various degrees, and their greater diameters are upon the average parallel with the secondary structure. In many cases the feldspar crystals are fractured in a direction diagonal to the cleavage, and in some cases in a single feldspar crystal there are two sets of diagonal fractures approximately at right angles to each other and each inclined about 45° to the cleavage.

(3) *Distortion of volcanic textures.*—Ancient volcanics, particularly of pre-Cambrian age, rarely occur over considerable areas without showing cleavage structure in part. In the Lake Superior country a greenstone with original ellipsoidal parting frequently shows a flattening of the ellipsoids in one direction, with or without fracture, and in such cases the ellipsoids and matrix have a flow cleavage parallel to the longer diameters.[c] In the pre-Cambrian rocks of Lake Superior are many schistose volcanic rocks containing amygdules and spherulites. The elongation of the amygdules[d] and spherulites in planes parallel to the cleavage in the rock is of common occurrence. The elongation of spherulites and perlitic textures may be particularly well observed in certain areas of isolated pre-Cambrian volcanics in the Fox River Valley of Wisconsin. Here there is also an agreement in direction between cleavage and the greater diameters of the distorted fragments of a volcanic breccia. Harker[e] describes the agreement in direction of cleavage and flattening of the fragments in a schistose volcanic ash in the boulder clay at Nantlle. In specimens from the Black Hills, and from the Menominee district of Michigan, the flattening of fragments in breccias is to be observed.[f]

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[a] See figs. 1, 4, and 5, Pl. I, Lehmann's Atlas, cit.

[b] Van Hise, C. R., Deformation of rocks: Jour. Geol., vol. 4, 1896, p. 460.

[c] Clements, Mon. U. S. Geol. Survey, vol. 36, Pl. XI.

[d] Sp. 27750, Crystal Falls district, Michigan.

[e] Sp., 14823, Black Hills, South Dakota; sp., 25669, Menominee district of Michigan.

[f] Harker, Slaty cleavage: Rept. 55th meeting Brit. Assoc. Adv. Sci., held in 1885, published in 1886, p. 837.

(4) *Distortion of fossils.*—The elongation of fossils in the plane of cleavage has been observed in so many cleavable rocks that no reference will be made to the individual cases. Harker, in his article on slaty cleavage, cited, refers to a number of such cases. In these distorted fossils it has been observed that the mean axis of strain has been one of absolute elongation in many cases.

(5) *Distortion of beds and attitude of folds.*—Frequently there may be observed the thickening or thinning of a bed or layer of rock through the processes of rock flowage. Any cleavage which is present in such a distorted bed is likely to be normal to the shortening.

Folds often show the direction of shortening of the deformed rock mass. The well known relation of cleavage to simple folds, i. e., a position roughly parallel to their axial planes, shows plainly the development of cleavage normal to the greatest compression which the rock mass has undergone. Deviation from this attitude becomes apparent as shearing develops parallel to the limbs of folds, as discussed in a subsequent chapter (p. 152). Folds may be indicated by the distortion of bedding. Certain specimens from the Black Hills show that the bedding has been shortened in its own plane by minor crenulations, and the associated cleavage may be observed to be in all cases normal to the greatest shortening indicated by such folds.[a] Similar instances may be cited from the Lake Superior country and from almost any other district where cleavable bedded rocks, particularly slates, occur.

Sorby has figured and described undulations in a coarse sandy shale, which lies between beds of fine shaly slate showing cleavage but not folding. The axial planes of the undulation in the coarse rock coincide with the cleavage planes of the finer rocks. It is clear that the direction of compression as shown by the folds is at right angles to the cleavage planes in the slate above and below.[b] Harker says that similar phenomena may be observed in almost any of the slate quarries of northern Wales.

Folds may be indicated by the distortion of gneissic or original flowage structure. The distortion of gneissic banding in the pre-Cambrian gneisses is too common and widespread to need detailed reference.[c] Wherever, with this folding, a subsequent cleavage has been developed, this appears in planes normal to the shortening of the rock mass shown by the folds.

(6) *Relations to intrusives.*—Intrusions of great masses of igneous rocks, and particularly deep-seated batholiths, are known to compress the adjacent rocks in directions normal to the periphery of the intru-

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[a] Sp. 14974, sl. 7712, Black Hills, South Dakota.

[b] Harker, Slaty cleavage: Rept. 55th meeting Brit. Assoc. Adv. Sci., held in 1885, published in 1886, p. 824.

[c] Van Hise, C. R., Principles of pre-Cambrian geology, Pls. CX and CXVII and fig. 162. Lehmann, Atlas, Pl. XIV, figs. 2 and 4; Pl. XVI, fig. 1.

sive masses. Cleavage is commonly developed in the surrounding rocks parallel to the periphery of the intrusive masses. Its development in planes normal to the greatest compression is thus clear. An illustration, cited by Van Hise, is the Black Hills batholith of granite which has intruded a sedimentary series, and developed a cleavage parallel to the periphery of the granite.

(7) *Relations to fractures.*—Where fractures and cleavage have been developed simultaneously, as is possible in heterogeneous rocks, the displacement along the fractures may indicate the direction of shortening and elongation of the rock mass as a whole. This is partially covered in the above discussion of the distortion of pebbles, crystals, etc. Even if the displacement can not be observed, the position of the fractures may indicate the probable direction of the compression of the rock mass, for fractures are ordinarily developed in planes inclined to such compression, and hence when the cleavage plane is inclined to the planes of fracture (figs. 9, 16, 17) the presumption is that it is not in the shearing planes, but more nearly normal to the compression of the rock mass. This criterion affords only a suggestion of the relations of cleavage to shortening of the rock mass, for the precise relations vary with the nature of the deformation, as shown in subsequent chapters.

GENERAL.

From the lines of evidence above cited it appears that wherever the directions of shortening and elongation of a rock mass can be determined with certainty any flow cleavage which may be present is normal to the total greatest shortening which the rock has undergone. The greatest, mean, and least diameters of the particles may be observed to have a tendency toward parallelism with the greatest mean and least axes of strain in the rock mass.

But there are minor deviations from parallelism, some of which are due to the heterogeneity of the rock mass and some of which are due to the manner of deformation.

Says Van Hise: "It is a very common phenomenon in slates and schists, both macroscopically and microscopically, for the direction of the secondary structure to wrap around the harder particles. As a hard grain or pebble is approached the cleavage structure in the matrix opens out on each side of the grain, envelops it, and closes in again beyond it. The structures nowhere intersect, although upon opposite sides of a particle near the ends they converge, and in passing toward either end they turn and become parallel."[a]

In a few and rather exceptional cases, where the parallelism of the longer diameters of the mineral particles is clearly the result of granulation or slicing, as in certain sheared conglomerates and sheared

[a] Van Hise, C. R., Deformation of rocks: Jour. Geol., vol. 4, 1896, p. 460.

anorthosites described in foregoing chapters, the longer diameters of the particles may show uniform, though slight, tendency to deviate from parallelism with the elongation of the rock mass, as shown by the nature of the strain or by the position of the longer axes of other particles present which have received their position parallel to the elongation of the rock mass by recrystallization.

In Chapter VI it will be shown that the longer diameters of the mineral particles sometimes deviate from parallelism with the elongation of the rock mass as a whole, because of the changing relations of the strain to the stress producing it during a rotational strain.

The deviations from parallelism under these conditions might be considered as evidence that the parallel structure is developed in shearing planes or planes of maximum tangential strain inclined to the greatest elongation of the rock mass, for where the rock has been much shortened even structures developed in shearing planes may vary only a few degrees from parallelism to the elongation of the rock mass. But the deviation may be adequately explained otherwise. (See following chapter.) It is certain that in the absence of the modifying conditions referred to the parallelism of the longer diameters of the mineral particles and the longer axes of strain in the rock mass is close, and that no uniform deviation can be detected either by microscopical or macroscopical observation.

It is clear from phenomena of the kind above described that an excellent cleavage may develop with but a comparatively small shortening of the rock mass. But the excellence of the cleavage seems to be more a matter of the nature of the mineral constituents (each of them having its own uniform influence on cleavage) than a matter of the amount of deformation which a rock has undergone. Where the conditions have been favorable to the development of minerals such as mica and chlorite, for instance, a comparatively small amount of shortening of the rock mass has developed a good cleavage, while, on the other hand, a very considerable amount of shortening has sometimes failed to produce anything but a poor cleavage in a rock consisting mainly of quartz particles.

It is of interest to ascertain whether the mean axis of strain represents actual elongation or shortening of the rock mass. Many instances of elongation of the mean diameters may be cited in the distortion of original crystals, in the distortion of pebbles of conglomerates, in the distortion of original volcanic textures, and in a few cases in the distortion of folds. The shapes of newly developed minerals, and especially those of mica and chlorite, are themselves suggestive of the nature of the strain which the rock has undergone. The greatest and mean diameters of the mica and chlorite plates have practically the same dimensions, and if the greatest diameter represents elongation, as it does beyond reasonable doubt, the mean diameter also represents elongation. Instances of shortening of the mean diameter also may be observed in the distortion of all of the forms above named, and the shapes of certain minerals newly developed are again suggestive of shortening of the mean axes of strain in the rock. In hornblende the greatest diameters are far greater than the mean and least diameters, which do not differ widely from each other. If the least diameter represents a shortening of the rock mass it seems likely that the mean diameter does so also, leaving only one direction of elongation parallel to the longest diameter of the hornblende crystals. The shapes of the mica and hornblende crystals so characteristic of cleavable rocks is taken as one of the best criteria for determining the nature of the strain, and one is tempted to go even further and say that when the chemical and physical conditions are favorable for the development of either mica or hornblende, mica may develop when the conditions are such that there is elongation along the mean axes of strain in the rock and hornblende when there is shortening along the mean axes of strain in the rock. A review of the facts seems to indicate that in the development of cleavage there has been, for the most part, an actual elongation of the mean axes of strain in the rock rather than a shortening, and that the relative importance of elongation and shortening of the mean axes is about the same as the relative importance of mica and hornblende in the production of rock cleavage.

CHAPTER VI.

RELATIONS OF THE ELONGATION AND SHORTENING OF ROCK MASSES, AND HENCE OF FLOW CLEAVAGE, TO STRESS.

Thus far in the discussion there has been a basis of observed geological fact. It has been possible to observe the causal relation between parallel arrangement of mineral particles and flow cleavage, and between the parallel arrangement of the mineral particles and the direction of elongation and shortening of rock masses. It is not possible to observe directly the relations of cleavage to the stresses which have deformed the rock, but as the relations of cleavage to the elongation and shortening of rock masses are known and as the relations of elongation and shortening of solid bodies to deforming stresses may be worked out in their simpler aspects, both experimentally and mathematically, and are accepted as proved in physical and engineering treatises, the general relations of cleavage to the stresses producing it may be stated with some confidence. The first step in the discussion, then, is a summary of the simpler and most obvious relations of deformation of solid bodies to stress.[a]

STRAIN.

Strain means any change in the relative position of the particles of a body. The change may be either of form or volume, or both. When the form changes the strain is called distortion. When the volume changes, the strain is called dilatation.

Any small sphere in an unstrained mass becomes an ellipsoid after strain—i. e., a strain ellipsoid, the greatest, mean, and least axes of which are called the principal axes of strain. In a special case (simple dilatation) all diameters of this sphere are changed equally and the resulting ellipsoid is a sphere. If these axes remain constant in direction during strain, the strain is called "irrotational" strain; if not, it is called "rotational" strain.

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[a] Hoskins, L. M., taken mainly from "Flow and rupture of rocks": Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 845–872.

Van Hise, C. R., Principles of North American pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, p. 636.

Thompson and Tait, Natural philosophy.

Becker, G. F., Finite homogeneous strain, flow, and rupture of rocks: Bull. Geol. Soc. America, vol. 4, 1893, p. 22; Jour. Geol. vol. 4, 1896, p. 430.

Young, Thomas, A Course of Lectures on Natural Philosophy and the Mechanical Arts, London, 2 vols., vol. 1, 1807, p. 135.

Peirce, C. S., Manuscript report to the Director of the U. S. Geol. Survey, 1897.

Any irrotational strain in which all three principal axes are changed in length in such a ratio that the volume remains constant, has been called "pure shortening" by Van Hise,[a] and this term will be used below. In a special case of irrotational strain without change of volume, one of the axes may remain unchanged in length; then the strain is known as a "simple shear" (Thompson and Tait[b]), or a "pure shear" (Becker[c]), or a "simple detrusion" (Young[d] and Peirce[e]). An irrotational strain is illustrated in two dimensions in figs. 28 and 29. Every particle of the body takes part in the deformation.

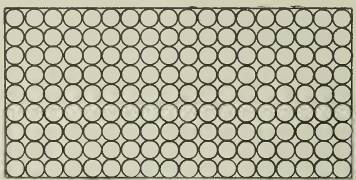

Fig. 28.

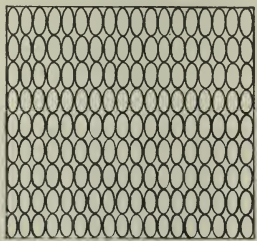

Fig. 29.

Figs. 28 and 29.—Diagrams showing irrotational strain (pure shortening).

A rotational strain occurring without change of volume is illustrated by the deformation of a rectangle A—B—C—D (fig. 30) into a parallelogram A—B—C′—D′ whose base and altitude are equivalent to those of the rectangle. All lines parallel to A–B move parallel to it through distances proportional to their distances from A–B. It is a strain analogous to that assumed by a deck of cards in which each card has been slipped a small amount over the card next below. While there is differential movement between the planes, there is no distortion in the planes themselves. The strain is equivalent to an elongation and a shortening at directions at right angles to each other combined with a rotation. This strain has been called "simple shear" (Hoskins, Van Hise) and "scission" (Becker). Peirce, in the report referred to, prefers the term scission, and in the following discussion the term scission will be used. The plane of scission referred to on subsequent pages corresponds to the plane of slipping between the cards in the above illustration.

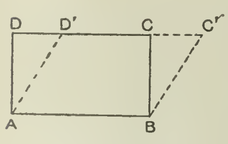

Fig. 30.—Diagram showing scission.

It has been proved that scission is equivalent to a pure shortening combined with a rotation of the body as a whole. In fig. 32 the flat-

[a] Van Hise, C. R., Principles of North American pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, p. 636.

[b] Thomson and Tait, A Treatise on Natural Philosophy, 2d ed.

[c] Becker, G. F., Jour. Geol., vol. 4, 1896, p. 430.

[d] Young, Thomas, A Course of Lectures on Natural Philosophy and the Mechanical Arts, London, 2 vols., vol. 1, 1807, p. 135.

[e] Peirce, C. S., Manuscript report to the Director of the U. S. Geol. Survey, 1897.

tened ellipsoids have the position they would have if flattened by shortening along the direction P Q and then rotated until the line P Q takes the direction P′ Q′.

Given any strain ellipsoid, it is impossible to determine from the ellipsoid itself whether it was produced in its present position by a

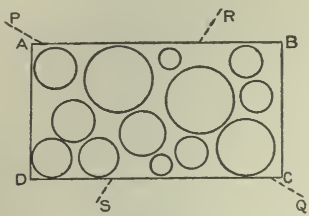

FIG. 31.

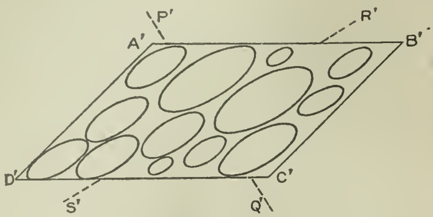

FIG. 32.

FIGS. 31 and 32.—Diagrams showing equivalence of a strain-ellipsoid in scission to a strain ellipsoid in pure shortening combined with a rotation.

pure shortening, by pure shortening combined with rotation—by scission—or by any combination of these strains. For proof of this relation of scission to pure shortening see Hoskins.[a]

Rotational and irrotational strain may be combined with each other in any proportion, and either or both may be combined with a dilatational strain. All strains may be referred to these types of strain or some combination of them.

STRESS.

Stress is the action and reaction between two adjacent parts of a body. When a condition of stress exists at any point in a body there are always three rectangular planes, upon each of which the resultant stress is normal. Three intersecting lines normal to these three planes, respectively, are called the principal axes of stress.

The difference in the intensity of the greatest and least of the stresses acting on these three mutually perpendicular planes is called the stress difference.

A shearing stress is a stress acting tangentially to the plane separating two adjacent portions of a body between which there is a stress. This is always present on all planes except the three principal planes, unless the three principal stresses are of equal intensity and of the same kind. Since in any possible stress condition three rectangular planes through any given point are free from tangential stress, any possible stress may be regarded as equivalent to three normal stresses whose directions are mutually perpendicular.

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[a] Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 862–865.

RELATION OF STRESS TO STRAIN.

In isotropic material, the axes of the strain that is occurring at any instant are coincident with the stress axes. If the stress axes remain constant in direction, the total strain will have its axes coincident with the stress axes; but not otherwise. Rotational strain in isotropic material will not occur unless the directions of the principal stresses vary. In irrotational strain the greatest, mean, and least axes of strain correspond, respectively, with the least, mean, and greatest axes of stress throughout the deformation. In a rotational strain the strain ellipsoid at any instant is the net result of all the strains developed at successive stages of the deformation; it is a compromise between the strain ellipsoid which is tending to be formed by the stresses then effective and the strain ellipsoids previously formed and rotated. Thus the directions along which elongation and shortening in the mass are occurring at any instant in rotational strain are not parallel to the axes representing the net result of all the elongation and shortening which the mass has undergone since the deformation started. At any instant the tendency toward shortening is in the direction of the greatest of the stresses, but the accompanying rotation prevents the continuation of the same relation of the stress and strain axes, and the axis of the greatest total shortening may be at that instant at any angle to the greatest axis of stress or the axis of shortening then occurring. When deformation occurs by fracture the fractures develop in planes inclined to the greatest principal stress as an expression of shearing stresses.

APPLICATION OF GENERAL PRINCIPLES OF RELATIONS OF STRAIN AND STRESS TO ROCK FLOWAGE AND FLOW CLEAVAGE.

Knowing the relations of flow cleavage to the axes of strain in a rock mass, the simpler relations of flow cleavage to stress may be deduced. These may be considered under two heads—(1) the cleavage strictly parallel to the axes of elongation of the rock mass, (2) the cleavage exceptionally inclined to such axes.

(1) Where cleavage is strictly parallel to the axes of elongation of the rock mass, as it is for the most part where the structure is due to recrystallization, and thus in the great majority of rocks with flow cleavage, the term flow cleavage may be substituted for the strain it represents in the above statement of the relations of strain and stress. In other words "plane of cleavage" may be substituted for the plane of the greatest and mean axes of the strain ellipsoid or "axis of cleavage" (when linear parallel) for the greatest axis of strain. The relations of flow cleavage to stress then may be stated as follows:

During irrotational strain, flow cleavage tends to develop uniformly in the plane normal to the greatest principal stress, or parallel to the least and mean stresses, or if linear parallel cleavage, it develops along the axis of least stress.

During rotational strain flow cleavage tends to develop at any instant in planes or lines normal to the greatest stress or in planes or lines in which elongation is occurring at that instant. But the cleavage tending thus to be formed is almost immediately rotated from its position normal to the greatest principal stress by variation in relative direction of the stress axes and strain axes, and becomes inclined to the plane or line in which new cleavage subsequently tends to develop. In other words, cleavage is at all times tending to develop normal to the greatest pressure in a rotational strain, but rotation constantly carries it from this position. Just as the total elongation of the rock mass in rotational strain is the net result of all the strains developed at successive stages of deformation, so cleavage, which by observation is approximately parallel to the final elongation of the rock mass, is the net result of all the strains, and its average position may be finally inclined somewhat to the greatest principal stress.[a]

It is probable that either dilatational strains alone or irrotational strains alone are of rare occurrence in a rock mass. The first of these requires three and the second two pairs of forces acting at right angles to one another with identical intensity. The common strain in nature is a combination of the forms of strain here called pure shortening, scission, and negative dilatation. These strains may occur simultaneously or at different times, or the same strains may recur several times. But the final result in any case is a strain ellipsoid, whose axes have relations to stress somewhat intermediate between those above described for pure shortening and for scission; in other words, for a rotational and irrotational strain. Hence the final position of cleavage is usually inclined to the axis of greatest stress of the force which has produced it, although tending throughout to develop normal to this axis.

Given a strain ellipsoid, there is no way of determining what stages or manner of deformation the ellipsoid has undergone to reach its present configuration. Likewise it may not be certainly determined what combination of stress and strain conditions have been present throughout the development of a given cleavage, although the relation of cleavage to the final total strain may be known. But it is believed that cleavage sometimes gives evidence of variations in stress and strain conditions during its development. Flow cleavage is dependent upon the parallel arrangement of its mineral constituents. If it be granted that these constituents have developed during successive

[a] In Daubrée's experiment cleavage was produced parallel to the elongation of the clay mass which was forced through a cylinder. While the relations of stress and strain are complex in such a case, there is nothing in Professor Daubrée's discussion of the subject which would indicate a development of the parallel arrangement under any laws different from those here summarized. (Loc. cit.)

stages of deformation of the rock mass, as they undoubtedly have, then if the strain has been a rotational one the particles developed at successive stages ought to lie at slight angles to one another. The recrystallized particles forming at any instant with their greater diameters exactly normal to the pressure during a rotational strain are constantly being rotated from this position. The result is that the longer diameters or direction of growth of particles developing by recrystallization at any instant normal to the greatest pressure do not quite correspond with the longer diameters or direction of growth of particles developed by crystallization in preceding instants, for these latter have been rotated from the most favorable positions. This is believed to be the main explanation of the feathering out of mica laminæ diagonally against one another where there are no other rigid particles present to cause local variation in stress (Pl. II, *A*, and figs. 2, 3, 4). The fact that the diagonal lapping of mica plates against one another occurs around rigid particles shows it to be a phenomenon caused by difference in stress directions, and hence its occurrence where such particles are absent offers evidence of its formation under changing stresses.

That cleavage by observation shows so little variation because of rotational strains may be due to the fact that recrystallization or granulation in later stages may have obliterated evidences of cleavage formed during the earlier stages of a rotational strain, or, more probably, to the fact noted on a subsequent page that the very development of parallel particles by recrystallization during rotational strain so modifies the stress conditions within the mass that the plane of easiest development for newly developing particles keeps up with the rotation to a greater extent than it otherwise would.

Relative positions of original and newly developing particles during deformation.—From analysis during an irrotational strain the greatest elongation of the rock mass is uniformly normal to the greatest pressure, and hence this is the constant plane or line of growth of newly developing or recrystallizing particles. In the early stages any rotating original particles may, however, vary in position from nearly parallel to the greatest pressure to normal to it. It is only after the deformation has progressed to a considerable extent, even supposing the rotating particles to have considerable freedom of movement, that the rotating original particles formerly at angles to the plane or line of elongation, or what becomes the surface of rock cleavage, bring their greater diameters to approximate parallelism to that of the newly developing or recrystallizing particles in the plane of cleavage. Where there is considerable interference with rotation a considerable amount of deformation may not bring about parallelism of the rotated particles.

If the deformation of a rock mass is a rotational one, as it commonly is, in the early stages there is likely to be the same difference in position between particles with original random arrangement and the plane or line of growth of newly developing or recrystallizing particles. But in deformation of this kind, all particles, both the particles already present with random arrangements and the newly developing and recrystallizing ones, are being rotated toward the plane of scission. Particles with original random arrangement during a rotational strain may be rotated toward the plane or line of easiest relief or easiest crystal growth, or away from it, depending upon the original position of the particles with reference to the plane of easiest growth. Starting with an unstrained rock, it is of interest to note that a rotational strain sufficient to produce elongation of the mass, say, at 35° to the plane of scission, will not rotate a particle originally normal to the plane of scission to such an extent as to make its greater diameters correspond with those of newly developing particles.[a]

Whether the deformation is by rotational or irrotational strain a sufficient amount of it may bring about substantial parallelism of all particles, new or old.

While analysis would seem to indicate that the relative positions of original and recrystallizing particles during deformation may be somewhat as above, it is not at all certain that this is actually the case in the metaclasic rocks; indeed, evidence has already been adduced to show that evidence of the rotation of original particles is insignificant as compared with the evidence of recrystallization in developing a parallelism. So far as recrystallization does arrange the minerals there may be no intermediate stages of arrangement. There is seldom to be observed in cleavable rocks stages intermediate between random arrangement and parallelism. The parallel arrangement usually appears first fully developed along certain zones while the intervening zones are comparatively unmodified, and where it thus appears, there is abundant evidence of its development entirely by recrystallization. If it be true that the parallel arrangement is due largely to recrystallization, and that intermediate grades of arrangement, which the stress and strain conditions in the rock mass would necessarily develop from the rotation of original particles, are absent, then mere parallelism of the mineral constituents becomes presumptive evidence that the parallelism has been produced by recrystallization with relations to stress and strain above indicated. This evidence could not stand by itself were it not supported by detailed evidence discussed in Chapter III.

Effect of heterogeneity.—The above statements are based on the assumption that the rock mass undergoing rock flowage and developing rock cleavage acts essentially like a homogeneous body in its stress and strain relations; but a rock is commonly a heterogeneous body,

[a] Hoskins, L. M., Sixteenth Ann. Rept. U. S. Geol. Survey; Van Hise, C. R., Deformation of rocks: Jour. Geol., vol. 5, 1897, p. 186.

and hence there are minor variations in the stress and strain relations, under the law stated on a preceding page that "in an isotropic material the axes of the strain that is occurring at any instant will, in general, differ in direction from the stress axes, the strain being in part governed by the structure of the material." The general effect of rigid particles is to transmit stresses locally in directions normal to themselves. The mesh structure which is frequently seen around the peripheries of large particles owes its origin to the local distribution of stresses caused by the influence of a rigid particle on the transmission of forces. Here is additional and most positive evidence of the development of cleavage in planes normal to the greatest stress, for it is evident that stresses are generally transmitted by rigid particles in directions normal to their peripheries. The feathering out of mica laminæ diagonally against one another about rigid particles, as described on pages 25–26, is probably to be explained in this manner.

Frequent reference has been made to the slicing or fracturing of rigid particles in planes, sometimes intersecting, that are inclined 45° or thereabouts to the plane of rock cleavage conditioned by the parallel arrangement of the micas and other constituents (see figs. 16, 17 and Pl. XI, *B*). As fractures develop in shearing planes inclined to the principal stresses, the presence of fractures inclined to the rock cleavage is itself evidence of the development of the prevailing cleavage in planes normal to the greatest stresses.

The influence of rigid particles in the transmission of forces during rotational strain is of interest: There is supposedly a rotation of the greater diameters of all particles, original and recrystallized, toward a common plane. These particles all act as transmitters of forces. The rotation being all in the same angular direction, the change in direction of transmission of pressure due to the rigid particles, is also all in the same direction. Hence, so far as rotation tends to bring about parallelism of the longer diameters of the particles themselves, it also tends to bring about parallelism of the transmitted pressures in a direction more nearly normal to the plane toward which the particles themselves are being rotated. Particles newly growing under these local transmitted stresses thus tend to bring their longer diameters more nearly into the plane which the rotated particles are approaching than they otherwise would. Particles newly developing under rotational strain are constantly being rotated from a direction normal to the greatest pressure of the rock mass, and hence from a position favorable to easiest growth, and because of rotation they are not parallel to the direction of growth of succeeding stages. But, so far as the particles themselves affect the transmission of forces, they tend to transmit forces such that newly developing particles in succeeding instants will develop in planes more nearly parallel to their own rotated planes than they otherwise would. For instance, suppose the longer diameters of a newly developing particle in fig. 33 to have the position AB in a rotational strain. At a later period the longer diameter may have the direction A′B′. If the stresses remain constant in direction, the plane of easiest growth still remains more nearly parallel to AB than to A′B′; in other words, the particle has been deflected from a position most favorable to its growth under the given stress conditions. But the rotating particle itself influences the direction of the transmission of stresses, with the result that a particle CD, newly developing under the influence of such local stresses, would tend to take a position not parallel to AB, but more nearly parallel to A′B′. This is made clear by simple resolution of forces. R_n, the transmitted normal component of the principal stress is proportional to the cosine of the angle α. When the angle α is 90°, this component becomes zero. When the angle α is zero, the component R_n has the full intensity of the unresolved force.

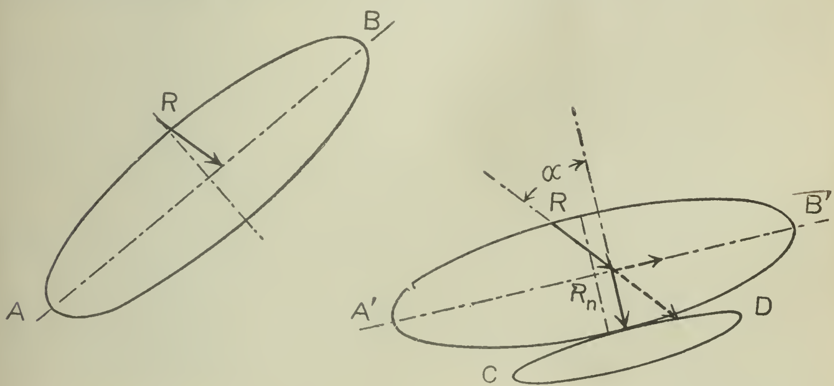

Fig. 33.—Diagrams illustrating rotation of particle during rotational strain and the resulting in change in direction of transmitted stresses.

Where the rock mass is made up of many rigid particles their influence may be of considerable importance in keeping newly developing particles in the plane of rotated particles previously present or developed.

A special case of the influence of rigid particles exists where the particles have a previous parallel arrangement. The deflection in direction of transmission of pressure will be uniform, and any newly developing cleavage may be uniformly in planes somewhat inclined to those of ordinary development of cleavage in a homogeneous rock without a previous parallel arrangement. Discussion of the relations of cleavage to previous parallel structures is made on pp. 151–152.

(2) Where the flow cleavage is due largely to granulation or slicing and the longer diameters of the mineral particles are uniformly, though slightly, inclined to the axes of elongation of the rock mass, the relations to pressure may exceptionally be somewhat different from those above cited. The fractures are the result of shearing stresses inclined to the greatest normal stress (pp. 111–112), and the carving of parallel grains in situ by the kind of fracturing known as granulation

or slicing, causes a cleavage which can be said to have developed in shearing planes inclined to the greatest pressure. The cleavage of the deformed anorthosite described by Adams (p. 37) may be partly formed in this way, and many rocks, as noted in Chapter II, show evidence of such development in certain minerals. Fig. 13 represents an unmashed anorthosite, and fig. 14 its mashed equivalent. The elongated feldspar particles in fig. 14 are clearly the result of carving in situ by the process of granulation or slicing along the sides. All stages of the process may be observed in the rock mass. That granulation or slicing does not occur in planes normal to the greatest pressure, but is uniformly in planes inclined to this pressure, is a well-established principle of mechanics, and hence we may conclude that the elongated particles of feldspar seen in fig. 14 may be really carved in situ in shearing planes and lie essentially in shearing planes of the rock mass. On this explanation the longer diameters of the particles can not be parallel to the elongation of the rock mass represented by CC in fig. 14. To bring about the deformation shown in fig. 14, it is not necessary to assume that the movement was entirely parallel to AA, for the same result may have been brought about by a movement parallel to BB, and in any given case it is practically impossible to tell what combinations of strain have occurred.

It has been shown (pp. 31 and 37) that as a result of granulation and slicing in intersecting planes at low angles to the greater strain axes of the rock mass residual grains may lie with their longer diameters essentially parallel to these axes—in other words, parallel to the prevailing cleavage. Such cases are covered by the general statements under (1) above.

Summary.—Commonly flow cleavage has been developed both by recrystallization and by granulation or slicing; recrystallization of certain minerals and granulation of others close by, in which case the parallel arrangement developed by recrystallization is mainly in planes normal to the greatest pressure as in (1) pages 112–117, and the parallel arrangement developed by granulation or slicing is developed in shearing planes as in (2) pages 117–118. In the early stages the inclination of the parallel structure formed by fracturing to the parallel structure formed by recrystallization is apparent (p. 38), and this deviation is excellent evidence of the truth of the conclusion that flow cleavage may be developed both in normal and shearing planes.

The fact may again be emphasized that the parallel arrangement caused in indirect planes by granulation and slicing is a subordinate and exceptional phenomenon as compared with that developed by recrystallization, and even where present frequently causes only a local variation of cleavage from planes conditioned by arrangement of crystallized particles; hence flow cleavage is for the most part developed in planes normal to the greatest pressure, and in but small part in shearing planes inclined to the greatest pressure.

PART II.

FRACTURE CLEAVAGE, COMPARISON WITH FLOW CLEAVAGE, SUMMARY STATEMENT OF CAUSES AND CONDITIONS OF SECONDARY ROCK CLEAVAGE.

CHAPTER I.

FRACTURE CLEAVAGE.

Fracture cleavage may be defined as a cleavage dependent for its existence on the development of incipient parallel fractures or actual fractures which by subsequent welding or cementation remain planes of weakness. It is obvious that the development of such a structure is confined to the zone of "rock fracture." Rocks may be fractured along parallel planes quite independently of any arrangement which the mineral constituents may have, and the fractures may be cemented by infiltration of foreign material, by crystallization of new minerals, and by recrystallization of adjacent minerals, or may be welded by bringing adjacent minerals by compression under bonds of molecular attraction. After welding the rock may still have a capacity to part along such planes more easily than along others, which capacity by our definition is truly a cleavage. Such cleavage has been variously called in its different aspects false cleavage, close-joints cleavage, strain-slip cleavage, fault-slip cleavage, ausweichungs cleavage, rift, and fissility. All of these terms may not have quite this significance, as will be shown below, but they have been used to designate structures essentially developed as above stated. The reader will doubtless recall many instances of quarry rocks, apparently massive, which on the stroke of a hammer break along definite planes nearly or quite independent of any parallel arrangement of the mineral constituents that may be present. In the ancient crystalline rocks it is not uncommon to find apparently solid graywackes and slates which break into polygonal or rhomboidal blocks along weakly cemented or incipient planes of fracture intersecting one another at uniform angles.

This may not be apparent in the solid ledge, but becomes apparent on weathering or when artificially broken. Cleavage of this kind is often excellent; the planes of parting are smooth, even, and continuous for some distance. A distinctive feature is its intermitted character, by which is meant its confinement to certain definite planes separated by considerable thicknesses of rock which show no tendency to cleave. Another distinctive feature is its presence in two or more intersecting planes rather than one plane. It is apparent that such cleavage may be present in rocks both with and without parallel arrangement of the mineral constituents, and in the former case it may occur either parallel to the longer diameters of the mineral constituents or at any angle to them. Where parallel to the mineral arrangement it is practically indistinguishable from flow cleavage (pp. 130–133). In other cases there is little difficulty in distinguishing the two. (See Pls. XVII–XXIII.)

FIG. 34.—Fracture cleavage in slate emphasized by ferruginous staining. There are 360 cleavage planes to the inch. After Dale.

Many illustrations might be cited of closely spaced parallel slips along one or two sets of planes which have been cemented or welded, forming a fracture cleavage. The structure described by Sorby (p. 17) as "close-joints cleavage" is for the most part so developed. The cementation of any of the widespread structures which Van Hise (p. 17) has called fissility, yields a capacity to party which comes under this head. Pl. XVIII, *B* illustrates a marble which has been sliced into thin parallel layers, the rubbing along the fractures being followed by the development by recrystallization of new mica and chlorite, cementing the rock and giving it a fracture cleavage. Dale[a] figures an excellent example of this structure in closely spaced planes. The so-called "false cleavage" is usually the result of closely spaced, parallel, overthrust folds grading into minute faults crossing a previously developed flow cleavage.[b] (See Pl. XIV, *B*.) The "ausweichungs cleavage" is a name applied to a similar structure caused by the development of minute overthrust folds passing into faulting. (See Pls. XX, XXI.) Slip cleavage and strain-slip cleavage are for the most part other names for phenomena of the sorts above described.

[a] Dale, T. Nelson, Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, fig. 91.
[b] Sp. 14974, Black Hills, South Dakota; sp. 42089, north shore of Lake Superior.

The rubbing along fracture planes incidental to the development of fracture cleavage frequently and usually results in slickensides or the development of parallel arranged minerals, such as chlorite and mica, and these may cement the partings. These minerals are clearly the result of recrystallization, and may be supposed to develop in the same manner as flow cleavage during a rotational strain or scission; that is, to develop in normal planes, but to be rotated almost at once toward the plane of scission, which in this case is the plane of the fractures. It may be said, then, that one of the incidental results of the development of fracture cleavage is a parallel dimensional arrangement of the mineral particles. This parallel arrangement, however, affects only a minute film of the rock along the parting planes, and may have no connection with the texture of the minerals in zones intermediate between the fractures. If the fractures be closely enough spaced it might happen that nearly all of the constituents of the rock might be arranged with their longer diameters parallel as the result of the rubbing along fracture planes, but it is argued on a subsequent page that very closely spaced planes of fracture are very exceptional and local, except where secondary to a previously developed flow cleavage, and that it is doubtful whether such fractures are ever closely enough spaced, independent of any previously developed parallel structure, to develop a parallel arrangement of the mineral particles comparable with that shown in fissile schists or slates. In practice there is certainly little difficulty, with few exceptions, in distinguishing the parallel arrangement developed as a result of rubbing along shearing planes from the parallel arrangement developed in normal planes and effecting all the constituents of the rock.

RELATIONS OF FRACTURE CLEAVAGE TO STRESS.

The relations of fracture cleavage to stress and rock deformation are different from those of flow cleavage. In the latter the parallel arrangement of the mineral particles, and hence the cleavage, is developed in planes or lines essentially parallel to the elongation of the rock mass. In the former the cleavage is developed in planes inclined to the elongation of the rock mass.

In any distortional strain there are necessarily shearing stresses in planes inclined to the greatest pressure. These do not receive expression unless there is fracturing, but whether or not there is fracturing the elongation of the mass at any instant is normal to the greatest pressure. If fractures occur in irrotational strains, these follow intersecting planes approximately 45° to the greatest pressure—planes of greatest tangential stress. This angle varies somewhat with the nature of the substance and the stress conditions. With a substance not ideally brittle it is probable that this angle is somewhat more than 45° to the greatest pressure.[a] With brittle substances the angle is probably less than 45°.[b] Where the two lesser stresses are equal, conchoidal fractures are produced such as occur in ordinary building stone tests. The displacement of the fractured parts results in elongation or shortening of the mass in such manner that the axes of the strain for the body as a whole, if it be still considered as a unit, have the same relations to pressure as those above stated for flow cleavage.

If fracturing occurs in rotational strains the fractures are in an intersecting set in such a position that the line of greatest pressure intersects the obtuse angles made by the fissures, and makes a smaller angle with the short side of the parallelogram of cracks bounding the column of rock than with the long side.[c] However, as in the case of irrotational strain, the displacements following the fracturing are such as to elongate and shorten the mass in the manner just indicated.

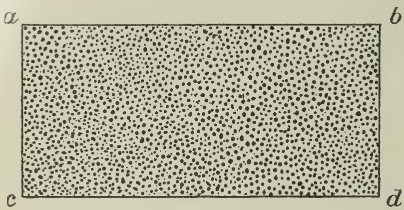

FIG. 35.

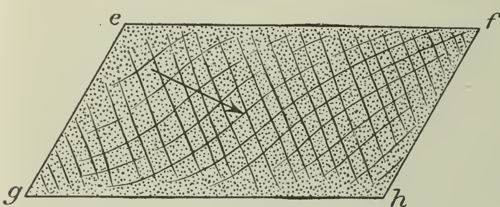

FIG. 36.

FIGS. 35 and 36.—Diagrams showing development of fissility, which, by cementation or welding, may yield fracture cleavage along the longer and shorter diagonals of the deformed portion of the rock stratum. After Van Hise. In the center of the stratum the fractures are in the planes of the greatest shearing, but on the outside of the layer the fractures are in lesser shearing planes, the direction of the fracture being controlled to some extent by bedding.

While in rotational strain the fractures may develop in two intersecting planes, they are likely to show differences in these two planes. If the rectangle *a–b–c–d* in fig. 35 be deformed to the parallelogram *e–f–g–h* in fig. 36, two sets of fractures will be formed, but in the direction *e–h* there is compression, and the rubbing along the fractures parallel to *e–h* produces slickensided surfaces, while along the diagonal *f–g* there is actual stretching of the material with the formation of cracks, and further deformation occurs more easily by the widening of these cracks than by the formation of new ones. The result is a fewer number of cracks normal to the longer diagonal of the rock mass than parallel to it. The curving of the fractures along the longer diagonal, shown in the figure, is due to the control and adjustment between bedding

[a] Becker, G. F., Finite homogeneous strain, flow, and rupture of rocks: Bull. Geol. Soc. America, vol. 4, 1893, p. 57.

[b] Becker, G. F., op. cit.; Hoskins, L. M., Flow and fracture of rocks: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896.

[c] Becker, op. cit., p. 55.

planes, which in this case are assumed to be more numerous on the outside of the layer.

The intermitted character of the fracture cleavage is a characteristic phenomenon of fractures in homogeneous rocks. Hoskins,[a] from an analysis of the mechanics of the problem, has concluded that closely spaced parallel fractures probably do not form through considerable volumes of a homogeneous rock with no previous parallel structure, no matter what the nature of strain; and that the extensive development of closely spaced parallel fractures must have been conditioned by some previous parallel mineral arrangement which has controlled the directions of fracture. In this Hoskins is followed by Van Hise,[b] who concludes from field observation that fissility developing in shearing planes is usually secondary to cleavage which develops in normal planes, although locally a fine fissility may develop independently of cleavage. If the stress conditions are such that the rock may yield by fracture, it does so along a few separated planes inclined to the greatest pressure, under the laws above noted. These planes once formed, further adjustment to pressure is easier by displacement along such planes than by the formation of new fracture planes. After there has been as much displacement as possible in the readjustment, the stresses may again accumulate so that the fractured parts are again fractured, but, owing to the displacement which they have undergone, the later fractures may not be quite parallel to the earlier ones. This is illustrated on a small scale by the fractures to be observed in granulation. While in the early stages of the fracturing of a given mineral particle belonging to one set in an intersecting system the fractures are approximately parallel, in later stages they are in any possible direction.

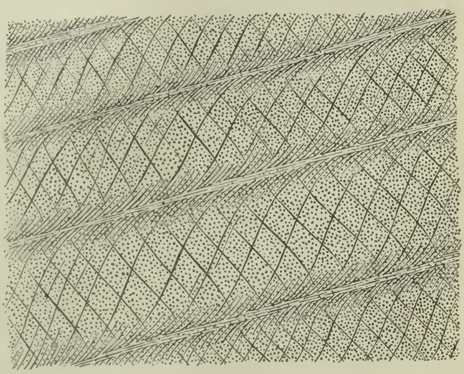

FIG. 37.—Fracture cleavage after fissility in bedded rocks, showing application of principles illustrated in figs. 35 and 36.

On the other hand, Becker[c] has maintained that parallel and closely spaced planes of weakness or fractures may and do develop independent of a previously existing arrangement of the mineral particles, the closeness of the spacing depending upon the wave length of the impulse producing the fracture.

[a]Hoskins, L. M., Flow and fracture of rocks: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, p. 873.

[b]Van Hise, C. R., Principles of pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 655–6.

[c]Becker, G. F., Finite homogeneous strain, flow, and rupture of rocks: Bull. Geol. Soc. America, vol. 4, 1895, p. 16.

There is practical agreement that closely spaced parallel fractures may and do develop, but there is not agreement as to causes or relative importance of the structure. Van Hise, on the one hand, maintains that such parallel fractures are for the most part easily discriminated from flow cleavage; that the structure has not been developed independent of a preexisting cleavage over any great area comparable in size to that in which original flow cleavage may be observed; and that the common development of this kind of structure is in planes somewhat separated by zones of noncleavable material. Becker, on the other hand, holds that closely spaced parallel fractures independent of any preexisting parallel arrangement do actually develop over wide areas; but when we remember that he regards flow cleavage, as well as fracture cleavage, as a structure developed in this way, the statement can not be set against that of Van Hise, for, as the present paper attempts to show, Van Hise and Becker are discussing different phenomena. An examination of the literature on the subject makes it clear that the cleavage variously called false cleavage, fault-slip cleavage, slip cleavage, ausweichungs cleavage, strain-slip cleavage, and rift, here grouped together under the term fracture cleavage, in a great majority of cases is a structure affecting well-separated planes with intervening zones of noncleavable material, and that only in exceptional instances and for limited areas does it occur in planes as closely spaced as the planes of flow cleavage and show external similarity to flow cleavage. From the observations which the writer has been able to make both in the field and laboratory, it seems doubtful whether fracture cleavage ever develops in planes as closely spaced as the planes of flow cleavage, as this is typically developed in slates and schists. Certainly by far the greater number of structures classed under the head of fracture cleavage show an intermitted character easily distinguishable from the closely spaced planes of parting of flow cleavage, and the statement is a safe one that fracture cleavage usually affects more widely separated planes than flow cleavage, and perhaps never affects planes so closely spaced as those of the most fissile slates or schists.

CHAPTER II.

COMPARISON OF FRACTURE CLEAVAGE AND FLOW CLEAVAGE.

Certain features of similarity and difference between fracture cleavage and flow cleavage have been already discussed, but they may be repeated as introductory to further considerations.

Fracture cleavage is conditioned by incipient parallel fractures or by the cementation or welding of parallel fractures, and the parallel arrangement of mineral constituents is in no way essential, although it may have been previously present or may be developed along thin films as a result of the rubbing along the parallel fractures. The planes of parting may be smooth and even, and may be equally good in two or more intersecting sets. They are commonly well separated by zones of noncleavable rock, but locally may be very closely spaced. The structure is developed in shearing planes inclined to the greatest pressure, under the normal conditions and laws of fracturing, in the portion of the lithosphere which Van Hise has called the zone of fracture.

Flow cleavage is always conditioned by the parallel arrangement of the mineral constituents, and is good in proportion to the excellence of the arrangement, the degree of the inequality of the axes, the arrangement of the mineral cleavages, and other features, as shown in Part I. The planes of parting are many and closely spaced, being separated only by the mineral particles or even by the cleavage plates of the mineral particles. The parting is usually parallel to one plane, but rarely in two or more intersecting planes, and in such cases one is far better than the other. The structure is developed in planes or lines parallel to the greatest elongation of the rock mass, usually with the same relations to pressure that the elongation of the rock bears. Flow cleavage is developed under conditions and laws of rock flowage in the deep-seated portion of the lithosphere which Van Hise has called the zone of rock flowage. The processes of recrystallization, granulation, and rotation are effective in flow cleavage, and not in fracture cleavage. The development of flow cleavage is accompanied by a diminution of volume through the development by recrystallization of minerals with higher specific gravity, a feature in which it differs from fracture cleavage, the development of which causes little change in the density of the rock.

EXPLANATIONS OF FLOW CLEAVAGE MAY NOT APPLY TO FRACTURE CLEAVAGE.

This is a self-evident proposition which scarcely needs discussion. Flow cleavage is by definition a cleavage conditioned by the parallel arrangement of the mineral constituents, and the causes of this arrangement are the causes of flow cleavage. Fracture cleavage is quite independent of a parallel mineral arrangement, except where superposed upon a preexisting flow cleavage, and hence the conditions and causes bringing about the parallel arrangement of mineral constituents are not processes and causes of fracture cleavage. Where fracture cleavage is superposed upon a previously existing flow cleavage the parallel arrangement of the constituents may have a strong modifying influence on the newly developing fracture cleavage, but the causes of the parallel arrangement can scarcely be said to be a cause of fracture cleavage; were the previous cleavage not present the fracture cleavage would develop, though perhaps not quite so readily or in the same planes or in planes so closely spaced. Again, the development of fracture cleavage may be accompanied by the rubbing of the sides against one another, developing slickensides or a parallel arrangement of the minerals in films adjacent to the fractures. The parallel arrangement in the films is probably developed largely through recrystallization as in rock flowage; indeed, the films may be said to have undergone rock flowage. Such a parallel arrangement is in no way essential to the existence of cleavage along the fracture planes; the welding of the fractures would yield a fracture cleavage as certainly if the parallel arrangement were not there.

EXPLANATIONS OF FRACTURE CLEAVAGE MAY NOT APPLY TO FLOW CLEAVAGE.

The reverse proposition that the explanation of fracture cleavage may not apply to flow cleavage is one of the essential points of this paper. King,[a] in 1875, emphasized the excellence of rock cleavage produced by the regelation of parallel joints, and showed that it possesses features in common with "slaty cleavage," supposedly due to parallel arrangement of the mineral constituents. He went still further and maintained that slaty cleavage itself is a close joint phenomenon, and that any parallel arrangement of the mineral constituents is merely an incidental phenomenon. Becker,[a] on a basis of experiment and mathematical analysis of the relations of stress to strain, has been positive in the statement that cleavage is not necessarily dependent upon the parallel arrangement of the mineral constituents, but can be induced as well in a homogeneous rock (a rock

[a] See discussion and references, pp. 14–15.

without discrete particles) as in a heterogeneous rock, thus implying that secondary cleavage in general may not be conditioned or caused by the parallel arrangement of the minerals. Doctor Becker recognizes the existence of a parallel arrangement of the mineral constituents in most cleavable rocks, but insists that this arrangement is incidental to rock cleavage, and is one of the results, not a cause or an essential condition. He maintains that cleavage is a capacity to part along certain planes along which the rock has been strained almost, if not quite, to the breaking point, giving it a weak cohesion along such planes, and that the development of a parallel arrangement of the longer diameters of the mineral constituents is possible only along and because of planes so formed, these furnishing directions of easiest relief.

It is here held that Doctor Becker's theory of the development of cleavage in shearing planes, which he applies to cleavage in general, applies only to what is here called fracture cleavage, and to this only with the modification that the parallel development of mineral constituents along shearing planes occurs as a result of actual rubbing after fracture has occurred rather than in planes of weakness along which no fracture has occurred. It is held also that Doctor Becker's theory will not apply to the structure here called flow cleavage, which is dependent on and conditioned by a parallel arrangement of mineral constituents, developed for the most part quite independently of shearing planes.

If Doctor Becker's view is the correct one, and the parallel arrangement of mineral constituents is a mere resulting incident and not a cause, then there would be no good reason why there should be any relation between the nature or excellence of the cleavage and the arrangement and shape of the particles themselves. The fact that there is this close dependence is shown by the following facts:

Flow cleavage always follows either the mineral cleavage or the peripheries of the mineral particles, or both.

The excellence of the flow cleavage varies directly with the degree to which the dimensional axes of the mineral particles approach parallelism.

The excellence of the flow cleavage varies directly with the degree of arrangement of the mineral cleavages.

The shape and dimensions of the particles in a rock with flow cleavage are always uniform and characteristic for minerals of the same kind, and thus not determined by the form of any preexisting plane or line of weakness.

Where a parallel arrangement of the mineral constituents is absent throughout the body of the rock any cleavage which may be present has the definite and distinctive characteristics above described for fracture cleavage, which are quite different from characteristics of flow cleavage. This is in itself sufficient evidence that the parallel arrangement of mineral constituents in some way affects the nature of rock cleavage.

It is known that the parallel arrangement of mineral constituents is developed under conditions of rock flowage, a process which, by observation and definition, occurs without fracture, and there is positive evidence, stated in Chapter III of Part I, that the parallel arrangement of mineral particles in flow cleavage has developed by processes entirely adequate to develop this parallel arrangement without the aid of previously existing parallel fractures.

It will be shown (Part III) that original cleavage presents analogies to flow cleavage. There can be no question that the parallel arrangement of minerals is the cause of original cleavage, and there can, further, be no question that this parallel arrangement is not determined by preexisting fractures in planes of weakness.

Hence, it is concluded that the parallel arrangement of mineral particles, far from being an incidental result of the development of cleavage is itself the fundamental condition for flow cleavage, by which is meant the structure, such as slatiness or schistosity, which is ordinarily referred to as cleavage.

That flow cleavage does not develop mainly in shearing planes in the manner of fracture cleavage is held to be shown by the parallelism of the longer diameters of the mineral particles and hence of the cleavage to the principal axes of elongation of the rock mass as a whole, evidence of which is presented in Chapter V, Part I. In this the writer only follows most other investigators of the subject. Doctor Becker would contend, because of the amount of shortening which the rock mass has undergone, that the longer diameters of the particles, developed according to his theory, would frequently incline so little to the principal axes of elongation of the rock mass that this inclination would be overlooked, and that the minute inclinations actually observed between different particles in a cleavable rock are explained by their development in inclined planes. It is believed that these slight variations, which are unquestionably present, have a subordinate effect upon cleavage (p. 118), and may be partly explained by local variations in stress because of the heterogeneity of the rock (pp. 106–108) and that the variations are too irregular to be explained by Doctor Becker's hypothesis.

Further, according to mechanical analysis by Hoskins,[a] it may be doubted whether closely spaced fractures or planes of weakness, required by Becker's theory, form in a homogeneous rock independent of a previouly existing parallel arrangement, and the observed

[a] Hoskins, L. M., Flow and fracture of rocks as related to structure: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 845–874.

facts intensify this doubt. Any cleavage and resulting parallel arrangement thus developed is likely to be in well-separated planes. The parallel arrangement of flow cleavage affects all of the constituents in all planes, is not confined to separated planes of parting, and shows no evidence of actual rubbing (except when followed by subsequent fracture cleavage).

Doctor Becker[a] has described the artificial development of cleavage in the flattening of ceresin cylinders and has held this cleavage to be in shearing planes. Unfinished experiments of a similar nature, begun by Doctor Becker and the writer jointly, do not seem to the writer to show the parallelism of cleavage to shearing planes. Indeed, the flattened cylinders of ceresin cleave directly parallel to the flat sides, with only such minor variation near the edges as would be explained by the inclined stresses developed there through the compounding of

Fig. 38.—Diagram showing the theoretical position of strain ellipsoids in quadrant of ceresin block flattened between two plates with friction between quadrant of ceresin block and plates. After Becker, Bull. U. S. Geol. Survey, No. 241, Pl. III, fig. 11.

the normal stress flattening the mass and the inclined stress developed by friction of the mass with the plates confining it. The theoretical positions of the flattened strain ellipsoids in such a deformed disk are shown in fig. 38. The cleavage developed by splitting the plates seems to be absolutely parallel to the longer diameters of the strain ellipsoids as drawn in the figure. Furthermore, when shavings of the ceresin are examined it is found that it is not homogeneous, but is flecked with minute bubbles or cavities, which in the flattened disk have their axes parallel to the flat sides of the disk, to the strain ellipsoids as drawn in the figure,[b] and to the plane of cleavage developed by splitting the disk. These minute flattened air bubbles are apparently planes of weakness which control the cleavage of the mass in the same manner as minute parallel mineral flakes might control it. Because of these minute planes of weakness the experiments with ceresin apparently have no value in showing that a cleavage may be developed in a strictly homogeneous substance independent of any parallel arrangement of the mineral constituents.

[a] Bull. Geol. Soc. America, vol. 4, 1893, pp. 81-83; Bull. U. S. Geol. Survey No. 241, 1904.

[b] The photographs of cleaved ceresin disks on Pl. IV of Doctor Becker's bulletin seem to the writer fully to confirm the conclusions above reached. The crescentic breaking at the edge of the cake described as following the shearing planes according to his diagram, fig. 14 of Pl. IV, correspond equally well to the longer diameters of the strain ellipsoids shown in fig. 11 of Pl. III. On either theory crescentic parting must appear whenever the cleavage occurs on one side or the other of the medial plane of the disk parallel to the flattened sides, the only difference being that in one case the crescent-shaped edge of the disk bends away from the medial plane and in the other toward it.

On Doctor Becker's theory the cleavage ought in the centre of the disk to be in two intersecting planes considerably inclined to the flat surface of the disk. The observed cleavage actually runs through this portion of the disk readily in one set of parallel planes without change of direction other than a gentle curving parallel to the longer axes of the strain ellipsoids, as in fig. 38.

When a perfectly homogeneous substance is deformed by irrotational stress, under Doctor Becker's theory cleavage would tend to develop equally well in closely spaced intersecting planes. Cleavage equally good in two sets of very closely spaced intersecting planes has not been observed. If such planes are prerequisite to parallel arrangement of the mineral constituents, how shall a newly developing particle act at the intersection of these planes?

The same argument would apply in a rotational strain, although the planes of weakness developed along shearing planes would be mainly concentrated in one set and those in the intersecting set would be few and far between.

It is therefore concluded that secondary cleavage includes two distinct phenomena, here called fracture cleavage and flow cleavage, developed under different stress conditions, the one developing essentially in shearing planes and entirely independent of a parallel arrangement of the mineral constituents, the other developing essentially in normal planes and dependent for its existence on the parallel arrangement of the mineral constituents, and that any explanation of secondary rock cleavage, which does not take account of these distinctions, but treats cleavage structure as a unit, is sure to lead to confusion.

SUPERPOSITION OF THE TWO STRUCTURES AND GRADATIONS BETWEEN THEM.

As already noted, a rock in which fracture cleavage has developed (with, perhaps, incidentally and subordinately a slight tendency to parallel arrangement along slip fractures) may be brought under conditions favorable for the development of rock flowage, and a parallel arrangement of all the mineral constituents may develop, either parallel or at any angle to the previously existing fracture cleavage. The process of rock flowage being essentially through recrystallization, evidence of preexisting cleavage is likely to be obliterated, but in intermediate stages the fracture cleavage may remain. Instances may be cited of rocks which have been broken up into parallelopiped blocks by fractures in two intersecting sets of planes, these cemented, yielding a fracture cleavage, and the whole then strongly compressed, the intersecting planes of fracture cleavage being brought nearly into parallelism. On weathered surface erosion may work down along the fracture cleavage planes, leaving the intermediate areas protruding like pebbles in a mashed conglomerate. Indeed, a rock of this sort shows very close similarity to a mashed conglomerate, and in many cases, as in the acidic porphyries of the Vermilion Lake district of Minnesota, can be distinguished from true conglomerates only by the most careful observation. They differ from the true conglomerates in that pebbles and matrix show no variety; in that the pebble-like forms are nearly all the same size; and, finally, in that the planes of fracture cleavage intersect at acute angles around the ends of the pebbles, whereas in the true conglomerate deformed by rock flowage the cleavage, indicated by the longer diameters of the parallel-arranged mineral particles, does not intersect at the ends of the pebbles. King[a] supposed all cleavage to develop in this way by the compression of divisional fracture planes into substantial parallelism.

It is difficult to judge of the effect of fracture cleavage in determining the plane of newly developing flow cleavage, but it is likely that it has little effect, for during rock flowage the conditions of pressure

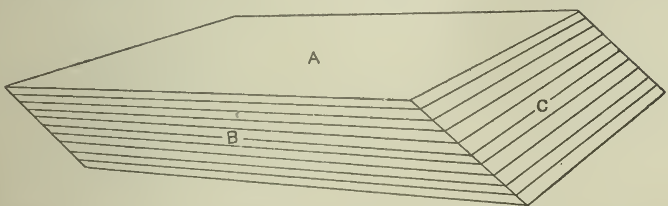

Fig. 39.—Diagram showing fracture cleavage parallel to B and C superposed on flow cleavage parallel to A.

are such that there is little opportunity for movement along shearing or fracture planes; the rock is elongated without regard to the existence of a previous fracture cleavage, and hence the parallel arrangement of the mineral constituents is developed without regard to the previous arrangement.

When flow cleavage comes under conditions of fracture we may have a fracture cleavage superimposed upon the flow cleavage, either parallel or inclined to it (fig. 39 and Pls. XXII, XXIII), and in this case the previously existing flow cleavage has a very marked effect on the position of the newly developing fracture cleavage. If the rocks were homogeneous the fractures would develop along intersecting planes of maximum shear, but the rock being already possessed of flow cleavage, the tendency is for the fractures to follow the cleavage planes already present, even if they are considerably inclined from planes of maximum shearing stress. Fracture cleavage is also likely to develop mainly in one plane parallel to the laminæ of a previously existing flow cleavage rather than along two or more intersecting planes, although the latter also occurs. As already noted, it is believed that a previously existing

[a] Trans. Royal Irish Acad., vol. 25, 1875, pp. 605-662.

parallel arrangement furnishes the conditions under which closely spaced parallel fractures ordinarily develop.

Evidence of slipping along the greater diameters of parallel-arranged particles in rocks with flow cleavage is often observed, and it is perfectly evident that such slipping is controlled largely by the parallel arrangement, and that the parallel arrangement is in no wise dependent upon the slipping, although it may be somewhat modified or emphasized by it. The cleavage in such a case is conditioned primarily by the parallel dimensional arrangement of the mineral constituents, and the additional episode of slipping parallel to such flow

FIG. 40.—Fracture cleavage crossing flow cleavage. After Dale.

cleavage is a modifying condition rather than a primary cause of fracture cleavage, which, if the flow cleavage had not been present, would develop, perhaps not so readily and in different planes. As a matter of observation, it is believed that it is practically impossible to tell in many cases whether or not flow cleavage has been followed by the development of parallel fracture cleavage.

False cleavage, fault-slip cleavage, slip cleavage, strain-slip cleavage, rift, and ausweichungs cleavage may all in part represent fracture cleavage superposed upon flow cleavage (Pls. XIV, *B* and XX), although the previous existence of a flow cleavage is not necessary. These structures characteristically develop along well-separated planes, and are frequently followed by the rubbing of the parts and the development of new minerals parallel to the fractures.

The so-called "grain" of slates may be in some cases the result of the superposition of fracture-cleavage on flow cleavage; at least a structure so developed has sometimes been called grain, but it is believed that for the most part it is due to weakness along the plane of the greatest and least diameters of parallel-arranged particles, and is a structure present in all rocks in which there is a good tri-dimensional parallelism of the mineral particles.

As folding and jointing or faulting may occur side by side, due to many varying conditions, though ordinarily developing in different zones, so we may have fracture cleavage and flow cleavage developing side by side, often with the most intricate relations. Folding commonly passes into faulting or jointing, and flow cleavage grades into fracture cleavage. In a given case it is frequently difficult to tell where one kind of cleavage begins and the other ends. Pl. XX, *A* illustrates a "fault-slip" cleavage. The layers of the rock have been minutely crenulated, and the folds have passed into minute fault-slips, the cementation of which by recrystallization of new minerals parallel to the slips has given a capacity to part along separated fault planes which is here defined as fracture cleavage. There has apparently also been developed a flow cleavage parallel to the axes of the minute folds, and it is exceedingly difficult to tell where the fracture cleavage ends and the flow cleavage begins.

RELATIVE IMPORTANCE OF FRACTURE CLEAVAGE AND FLOW CLEAVAGE.

It is very apparent from the above discussion of fracture cleavage and flow cleavage that they are correlative phenomena developed under different conditions. Flow cleavage is the better cleavage of the two in that it allows of closely spaced planes of parting, whereas fracture cleavage does not, and flow cleavage also is the kind which appears in rocks which we ordinarily associate with the term cleavage. The cleavage parallel to the longer diameters of particles in slates, phyllites, and schists is flow cleavage, and it is not necessary to argue that this structure is far more conspicuous, widespread, and characteristic of what are ordinarily thought of as cleavable rocks than the fracture cleavage developed in planes inclined to the longer diameters of the parallel minerals. Indeed, many writers use the term parallel arrangement of mineral particles and rock cleavage as essentially synonymous. Because of its manner of development flow cleavage obliterates evidence of previously existing fracture cleavage, while fracture cleavage is likely to emphasize, rather than to destroy, flow cleavage. It is concluded, therefore, that the most characteristic and widespread structure which we ordinarily think of as cleavage comes under the head of flow cleavage, but that there is also present abundantly in rocks of the lithosphere another kind of cleavage, here called fracture cleavage, developed under conditions quite different from those favorable to the development of flow cleavage, and not in any way dependent upon the parallel arrangement of the mineral particles.

CHAPTER III.

SUMMARY STATEMENT OF CAUSES OF SECONDARY ROCK CLEAVAGE.

Secondary rock cleavage is a property by virtue of which some rocks may be split along parallel surfaces and which is due to the weakness of molecular attraction along such surfaces as compared with the attraction in other directions. The property of cleavage is a capacity to part; actual partings are not included under this head. It is a phenomenon associated with the parallel arrangement of mineral particles, which in turn is induced during "rock flowage" under differential pressure. The relations of cleavage to the parallel arrangement of mineral particles; the relations of cleavage and parallel arrangement to differential pressure, and the processes through which the parallel arrangement of mineral particles has been brought about, have been matters of dispute among men who have attacked the subject from mathematical, experimental, and observational standpoints. The foregoing report is a presentation of evidence on this subject afforded by field and laboratory study of the structural and mineralogical characteristics of metaclasic rocks, with only incidental reference to the mathematical and experimental aspects of the question. It is believed that a sufficiently great variety and abundance of rocks have been examined, and that the facts observed are so uniform and significant as to warrant the following statement of the causes and conditions of secondary rock cleavage:

Secondary rock flowage is of two kinds, widely differing in essential causes and conditions. One has been called flow cleavage, because of its characteristic development during rock flowage, under conditions and laws of rock flowage and in the zone of rock flowage, and the other has been called fracture cleavage because of its characteristic development through fracture under laws and conditions governing fracture in the zone of rock fracture.

FLOW CLEAVAGE.

Flow cleavage conditioned primarily by the parallel arrangement of the principal diameters of unequiaxial mineral particles. It follows these principal diameters and thus intersects the fewest possible mineral particles. It is observed to vary in excellence with degree of arrangement, and with the inequality of the greater, mean, and least dimensional axes of the parallel arranged particles. It is linear parallel or plane parallel (parallel to a line or to a plane) and is in one plane or two intersecting planes (one of them representing grain), according to the degree of inequality of the greater, mean, and least dimensional axes of the parallel arranged particles. The ratio of the inequality of the axes has been found by measurement to be fairly uniform in particles of the same mineral species, and hence the particles of a mineral species wherever found with the same degree of arrangement have about the same effect in producing rock cleavage.

Flow cleavage is conditioned secondarily by the parallelism of the mineral cleavages of the parallel mineral particles. This is a condition clearly dependent upon the arrangement of the dimensional axes of the mineral particles; the dimensional axes of the particles must be parallel, if there is flow cleavage, while the mineral cleavages may or may not be parallel depending on the uniformity or lack of uniformity of their relations to the dimensional axes. Uniform relations are observed in cleavable rocks only where the particles have dimensions determined by uniform crystal habit, as in the micas, hornblende, chlorite, talc, rarely in feldspar, and in the group of characteristic but less abundant schist-making minerals which have been seen to have a poor dimensional arrangement, tremolite, staurolite, garnet, actinolite, chloritoid, andalusite, tourmaline, sillimanite, etc. So far as any of these minerals have dimensional parallelism there is a tendency toward parallelism of their mineral cleavages, and to this extent the mineral cleavage may cause a rock cleavage. The uniform relations of mineral cleavage to dimensions of the particles are not observed when the dimensions of the particles are independent of the crystal habit, as in calcite and the greater proportion of quartz and feldspar particles. In such particles the mineral cleavages are not parallel among different particles.

Parallel mineral cleavages may produce a flow cleavage in the same plane as that conditioned by the dimensional arrangement, as in mica and chlorite; parallel to the greatest axis of dimensional development, as in hornblende; or where the mineral has two cleavages one may aid the cleavage conditioned by the dimensional arrangement, while the other may give the rock a cross cleavage, as in feldspar.

Minerals of the same kind have a tendency to be concentrated into bands. As the minerals vary in their cleavage-producing capacity (that is, in shape, dimensional arrangement, and arrangement of their cleavages), the rock cleavage is likely to vary greatly in different planes, in some cases so widely that practically the flow cleavage is confined to a comparatively few and separated planes. When segregated in bands, also, difference in strength or cohesion of the different minerals may condition planes of weakness quite independent of the parallel dimensional arrangement.

According to the arrangement shown by the minerals, the parting following rock cleavage may be between mineral particles or through their mineral cleavages. If between the minerals, the flow cleavage may, for convenience in discussion of origin, be called intermineral or adhesion cleavage; if through the minerals because of their own cleavage, the flow cleavage may be called cohesion cleavage. In cleavable rocks as a whole probably intermineral cleavage is predominant; in the most fissile schists and slates both the intermineral and cohesion cleavages are present and the cohesion cleavage may be more effective than intermineral cleavage. In terms of individual minerals, intermineral cleavage is predominant in so far as quartz, feldspar, calcite, tremolite, actinolite, garnet, tourmaline, staurolite, chloritoid, andalusite, and sillimanite are present. Intermineral and cohesion cleavage together are effective in proportion to the amount of mica, chlorite, hornblende, and rarely feldspar, present.

The processes through which the parallel arrangement of minerals is brought about, are:

(1) Crystallization or recrystallization of minerals with their respective dimensions in common planes or lines, with or without contemporary or subsequent rotation. Evidence of this is conspicuous in the abundant parallel minerals which have been observed to afford the best flow cleavage, mica, hornblende, and chlorite, as well as in certain minerals which are less abundant in cleavable rocks and which have little effect on rock cleavage, such as calcite, tremolite, actinolite, garnet, tourmaline, staurolite, chloritoid, andalusite, and sillimanite. Evidence of recrystallization is present but less abundantly in certain parallel minerals, which have less effect on rock cleavage, such as quartz and feldspar.

(2) Rotation of all the particles in a rock toward dimensional parallelism. Rotation must always occur during the change in form induced by rock flowage. The evidence of rotation consists largely in the absence of evidence of other processes of parallel arrangement. On such evidence, rotation, while probably always present, is subordinate to recrystallization as a process of arrangement in the best cleavage-giving minerals, and is important only in minerals such as quartz and feldspar which have little effect in the production of cleavage when compared with mica, hornblende, and chlorite.

(3) Slicing and granulation, besides affording considerable assistance to recrystallization and rotation, are observed to yield a dimensional parallelism by themselves, by carving the original grains in situ into rough dimensional parallelism without any rotation, and by breaking slices from the mineral particles which, before any considerable rotation has occurred, may lie parallel. The longer diameters of particles arranged in a parallel position by these processes may be parallel or inclined to the longer diameters of particles developed in a parallel

position by recrystallization. These processes are observed to be of some little importance in arranging quartz and feldspar, and to a limited extent also are effective in arranging hornblende and mica. In any case, however, they are much less effective than either recrystallization or rotation and are important principally in the aid they give to recrystallization and rotation.

(4) Gliding, i. e., change of form by differential movements along definite planes in crystals without fracture. Evidence of this has been observed only in calcite, a mineral better adapted than any other to take a parallel arrangement through this process; yet even in this mineral gliding is clearly subordinate to recrystallization.

Relations of flow cleavage to differential pressure.—The simpler relations of stress to the directions of shortening and elongation in a rock mass during rock flowage are known. Observed relations of flow cleavage to such directions of shortening and elongation give the relations of the structure to pressure. Wherever the plane or line of elongation of the rock mass can be observed, the flow cleavage is observed to be approximately parallel to the greater elongation of the rock mass (or normal to the shortening), but is exactly parallel (with such minor deviations as are caused by the heterogeneity of the rock mass) only so far as the cleavage is conditioned by a parallel arrangement caused by recrystallization. Where the cleavage is locally conditioned by a parallel arrangement induced by granulation or slicing it may at times be inclined to the greatest elongation of the rock mass.

Where the cleavage is exactly parallel to the axes of elongation of the rock mass, the relations of the cleavage to pressure can be stated by substituting the term cleavage for the axes of strain which it represents. If the strain is an irrotational one (pure shortening and elongation with or without dilatation), the greatest elongation, and hence the flow cleavage, is always developed normal to the greatest pressure. If the strain is a rotational one (scission or scission combined with pure shortening and elongation, with or without dilatation), at any instant the rock mass is being elongated, and hence rock cleavage is being developed normal to the greatest pressure, but, due to rotation, the total elongation of the rock mass (which represents at any instant the net effect of the stresses producing it) and the cleavage immediately become slightly inclined from its normal position to the greatest pressure, and inclined from the position of new cleavage subsequently tending to develop in planes where elongation is then occurring normal to the greatest principal stress. Hence cleavage is always tending to develop normal to the greatest principal stress, but its final position may or may not be inclined to the greater stress depending upon the nature of the strain.

Where the cleavage is conditioned in whole or in part by the parallel arrangement caused by granulation or slicing and is not parallel to the axes of elongation of the rock mass, its development has been in shearing planes inclined to the maximum elongation of the rock mass.

To these simple relations of cleavage to pressure there are a number of modifications, due to the variation in local stresses caused by the influence of rigid particles on the transmission of stresses, and due to the limitations of the processes of rotation and recrystallization in bringing or keeping the greater diameters of the rock mass in parallelism with the greatest lengthening of the rock.

FRACTURE CLEAVAGE.

Fracture cleavage is a capacity to part along parallel planes, usually in intersecting sets, along which there has been either incipient fracturing or actual fracturing followed by cementation or welding. It is a structure developed in shearing planes inclined to the greatest pressure under the laws of fracture and in the zone of fracture in the lithosphere. Fracture cleavage may or may not be accompanied by a parallel arrangement of the mineral constituents, but a parallel arrangement is not essential to its existence, and when present is only a modifying condition or result and not a cause.

RELATIVE IMPORTANCE OF FRACTURE CLEAVAGE AND FLOW CLEAVAGE.

Flow cleavage and fracture cleavage are correlative phenomena. Flow cleavage is a structure characteristic of rocks which we ordinarily associate with the term cleavage, such as slates, schists, phyllites, etc., and flow cleavage affords planes of parting more closely spaced than fracture cleavage and usually in one plane rather than in two or more intersecting planes. Fracture cleavage is obliterated by the subsequent development of flow cleavage, while flow cleavage may be destroyed or emphasized by the subsequent development of fracture cleavage in the same rock. The structures known as fault-slip cleavage, false cleavage, slip cleavage, and ausweichungs cleavage are in most cases varieties of fracture cleavage which have been superposed on flow cleavage.

CHAPTER IV.

COMPARISON OF PRESENT STATEMENT WITH PREVIOUS STATEMENTS CONCERNING SECONDARY CLEAVAGE.

Sorby,[a] Heim,[a] Harker,[a] and others have considered cleavage to include two classes of phenomena similar to those described in this paper under "fracture cleavage" and "flow cleavage." Van Hise's[a] discussion of "cleavage" would apply almost in toto to what is here called flow cleavage, and his discussion of "fissility" would apply not only to the parallel closely spaced fracturing which he termed fissility, but to the cleavage, or capacity to part, developed by the cementation or welding of such fractures, or to what is here called fracture cleavage. The writer is thus essentially in accord with Sorby,[a] Heim,[a] and Harker[a] in distinguishing two classes of phenomena under cleavage; and by correlating fracture cleavage with fissility in part, he is in accord also with Van Hise. He differs from those who have attempted to discuss cleavage as a single kind of phenomenon resulting from a single group of causes and conditions. King[a] and Becker[a] in particular have applied to cleavage in general an explanation which is here held to apply mainly, with certain modifications, to what is here called "fracture cleavage," and Becker's strong presentation of fact and argument has had much weight. In this report especial emphasis has been laid on the proof that the two phenomena are separate, resulting from different conditions and causes, and that the explanation of fracture cleavage will not apply to flow cleavage.

That a parallel arrangement of mineral particles is an essential and adequate cause of flow cleavage (or "cleavage" as this term is used by many writers) has been assumed by all writers except King[a] and Becker.[a] The points here added or emphasized are the nature of the parallel arrangement of the mineral particles and the dependence of cleavage on the parallel arrangement where such arrangement is present, as follows: (1) The control of the arrangement of the mineral cleavages by the dimensions of the mineral particles; (2) a statement of the relative effects of dimensional and mineral cleavage arrangement in the particles of different mineral species; (3) proof of the uniformity in shape, dimensions, and cleavage-producing effect of

[a] See discussion of literature on pp. 13–15.

particles of the same mineral species; (4) a determination of the relative importance of the dimensional arrangement of the mineral particles and the arrangement of the mineral cleavages in producing flow cleavage.

Concerning the processes through which the parallel arrangement of the mineral constituents in flow cleavage has been brought about, no new conclusions are offered, unless certain modifications of old ideas may be called new, but evidence is presented to show to what extent the several possible processes are effective. Recrystallization was hinted at by Sedgwick when he referred to the parallel arrangement as due to "crystalline forces." Sorby stated that the development of minerals such as the micas in cleavage planes "may have been a subsequent operation." Sharpe explained the parallel arrangement by the flattening of the individual particles in situ.[a] Such a result is likely to be produced by recrystallization, but Sharpe makes no statement as to the process through which it is obtained. While a number of other writers have discussed the solution and deposition of minerals (recrystallization) as a process active in the deformation of rocks, Van Hise was the first to show the predominance of the process of recrystallization in the development of a parallel arrangement of the particles. Moreover, his conception of the process and the conditions favorable to it is much more definite than that of his predecessors. The facts observed in the investigation above described are in accord with Van Hise's statement. The new features are the presentation of a number of criteria for discriminating the effects of recrystallization from those of other processes, and through this means the presentation of an additional proof of the predominating importance of recrystallization when compared with other processes, and finally a proof of dimensional arrangement and control of mineral particles through this process.

The development of a parallel arrangement by the rotation of random particles was first held by Sorby, who has been followed by most other writers. The present statement contains nothing new on this subject except evidence of its subordinate importance as a process in arranging the mineral constituents.

Gliding has been shown by Adams and others to be of importance in the production of parallel arrangement of calcite in metaclasic rocks. It is believed that the facts stated in this report demonstrate that evidence is lacking to show the importance of this process in metaclasic rocks in general as compared with the other processes described.

The processes of granulation and slicing which produce a parallel arrangement of mineral constituents, have been described by Van Hise,

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[a] See references on pp. 13–16.

Adams, and others.[a] In this paper the writer has attempted to determine the amount and nature of the evidence of this process in the metaclasic rocks.

The statement of the relations of flow cleavage to the shortening of the rock mass and to pressure is essentially the same as that of practically all others who have assumed the parallel arrangement of mineral constituents to be a necessary condition for the existence of cleavage, and is especially similar to the statements of Van Hise and Hoskins, but it varies from the conclusions of King and Becker,[b] that all cleavage is developed in shearing planes inclined to the greatest elongation of the rock mass. An advance is made perhaps in showing the reasons for slight variations from parallelism to be seen in cleavable rocks and the effect of rigid particles on the local distribution of stresses within the rock mass.

The explanation of the development of fracture cleavage in planes of maximum shear or jointing here given is essentially the same as that applied by King and Becker, especially Becker, to all cleavage, both fracture and flow cleavage (pp. 126–130). Van Hise's explanation of the relations of pressure to fissility (pp. 126–133) apply almost without change to the present statement of the relations of pressure to fracture cleavage.

It must now be apparent to the reader that the conclusions of the present report have many features in common with those long ago reached by Sorby, but that they correspond more nearly in emphasis and form with those of Van Hise. Sorby suggested most of the factors in the problem; Van Hise showed their relative importance and the predominance of recrystallization. Aside from new features above referred to, the writer differs from Van Hise only in confining fissility strictly to actual partings as defined by Van Hise and in applying the term fracture cleavage to the capacity to part formed by the welding or cementation of fissility partings. To this restriction of the application of the term fissility, and to the use of the term fracture cleavage, Van Hise assents.[c]

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[a] See discussion and references, pp. 14–17.

[b] See discussion and references, pp. 18–19.

[c] See discussion and references, pp. 19, 126–130. See also Treatise on metamorphism: Mon. U. S. Geol. Survey, vol. 47, 1904.

PART III.

ORIGINAL CLEAVAGE.

[T]he term original cleavage may be used conveniently to designate the [cle]avage sometimes possessed by a rock on its first solidification from [m]agma, or deposition from water, as distinguished from secondary [cle]avage, which is produced by secondary processes accompanying [ro]ck flowage after the solidification or deposition of the rock. A brief [dis]cussion of rocks with original cleavage, or protoclases, is here [giv]en to show the main points of similarity and difference between [ori]ginal and secondary cleavage. Original cleavage is found in clastic [sed]iments and in certain igneous rocks with a banded or flow structure.

BEDDING IN CLASTIC SEDIMENTS.

[T]he bedding of sediments may be a capacity to part along parallel [sur]faces which, rather than an actual parting, is by our definition rock [cle]avage. Such cleavage is probably for the most part due to the dif[fer]ences which are found in the strength of the beds, and which allow [ru]pture to occur more easily along softer strata, usually of a shaly [nat]ure, than along hard layers. But it is certain that the cleavage in [me]chanical sediments is due also to a dimensional arrangement of the [mi]neral constituents. Waterworn particles or pebbles are commonly [no]t round, but ellipsoidal or subangular. While the shape, of course, [va]ries considerably with the nature and structure of the mineral or rock, [av]erages of the greatest and least diameters of a large number of peb[ble]s and of mineral particles from microscopic slides of finer sediment[ar]y rocks show a rough uniformity, not far from 2 to 1. Unexquiaxial [pa]rticles moved by water are deposited in a position determined by [the] configuration of the immediately underlying floor and by stresses [the]re obtaining. These stresses are those of gravity alone or of [gr]avity combined with moving water. The tendency is for gravity to [bri]ng the greater or mean axes of the particles toward a horizontal [pla]ne, assuming the floor to be horizontal, while that of moving water [is t]o lay the greater diameters of the particles at some angle to this [pla]ne, usually low, under the law that the ellipsoid tends to take such [a p]osition that it presents the greatest surface to stresses acting upon it. Their combined forces deposit the particles in such a manner that they sometimes overlap, in the manner of shingles. Gravity is greatly predominant in original deposition and has a tendency to produce a horizontal arrangement. This tendency is likely to be somewhat emphasized later by the weight of overlying rocks. The arrangement may be such that all three dimensional axes of the various particles are respectively parallel, or such that only the least axes are parallel, and the other two are axes parallel to a plane and not to one another, or such that the particles may lack all but a faint tendency toward parallel arrangement, depending upon the configuration of the floor and upon whether gravity alone, or gravity combined with moving water, produces the result. A tendency to dimensional arrangement of the particles is thus one of the characteristics of sedimentary bedding. The alternation of bands of varying coarseness and varying mineralogical composition is also a characteristic feature. When a sediment has been cemented to a coherent solid, the bedding is not an actual parting, but may remain a plane of weakness with a capacity to part, and hence truly a cleavage—a cleavage primarily due to the dimensional arrangement of unequiaxial particles. It is scarcely necessary to add that cementation may be so thorough that the rock does not part along bedding planes any more readily than elsewhere. In coarse rocks the parallel arranged particles themselves may be composite, and the individual minerals making up the composite particles may have neither dimensional nor crystallographic arrangement. In finer rocks the dimensionally arranged particles may be mineral individuals. In such particles parallelism of crystallographic properties may be found if there are uniform relations of the crystallographic properties to the dimensional diameters of the particles. The degree of this uniformity varies with the different minerals and with the length of time during which the particle undergoes the wearing of water. Quartz grains in a sedimentary rock show little if any crystallographic parallelism. Feldspar may do so rarely in arkoses, clays, and muds, where the shape of the feldspar particles is conditioned by the normal habit or cleavage of the feldspar. Mica, when original in sedimentary rocks derived from the disintegration of granite or other mica-bearing rocks, shows characteristic crystallographic parallelism. It may frequently be seen in cleavage plates lying parallel to the bedding of quartzites and shales. Hornblende has little arrangement, probably due to its breaking down by water action. Other minerals less abundant in sediments may or may not show crystallographic parallelism, depending largely on their crystal habit and the length of time they have been subjected to the working of water, but they are normally in such small quantities in sediments that their arrangement and influence on bedding cleavage need not be discussed.

In general, then, the parallel arrangement of particles in sedimentary bedding is dimensional, and either complete or partial, usually the latter, depending upon the nature of the stresses exerted at the time of deposition and the evenness or irregularity of the floor. Where the constituent particles of the sedimentary rock are separate mineral individuals rather than pebbles made up of many mineral individuals there is present in some cases a crystallographic parallelism, depending entirely upon the uniformity of the relation between the crystallographic properties of the crystals and their dimensions. The parting occurs parallel to the longer diameters of the particles, usually between particles and not along the mineral cleavage, although in the case of the micas, the rock cleavage may follow the mineral cleavage, as evidenced by the corresponding mica spangles to be seen on both faces of a parted quartz-slate in which the parallel structure is entirely that of bedding. Parting along bedding is aided also by the difference in nature and texture of different beds.

In all of these phenomena the parallel arrangement of sedimentary bedding is closely similar in kind to the secondary flow cleavage incidental to rock flowage. There are, however, differences in the phenomena shown by sediments and rocks with flow cleavage, some in kind but mostly in degree. In both rocks the segregation into bands of minerals or particles of the same kind or size are characteristic features, resulting in planes of weakness perhaps entirely independent of a parallel arrangement of the mineral constituents. The particles in the flow cleavage rocks due to granulation probably have sharper angularities than the angular particles in the sediments. The most characteristic particles in flow cleavage rocks, i. e., those developed by recrystallization, have more unequal dimensions than particles of the same minerals in a sedimentary rock, the water having a tendency to minimize the differences in dimension. Characteristic arrangement due to dimensions is, accordingly, on an average, poorer in sediments than in rocks with secondary cleavage, although the differing processes bringing about the arrangement in the two cases modify the results. The crystallographic parallelism in sediments is not so good as in rocks with flow cleavage, for the reason that the rounding effect of the water is likely to modify the uniformity of relations between dimensions and crystallographic properties. These latter differences, however are not great.

These are the differences shown by the minerals appearing in both the sedimentary and secondary cleavage rocks, but there is an additional and very important difference. The relative abundance of the different minerals varies. Quartz and feldspar are characteristic of sedimentary rocks, while mica and hornblende, etc., are subordinate. In the rocks with secondary cleavage mica and hornblende are the characteristic minerals, as well as a long list of minerals only sparsely present in sediments, such as chlorite, actinolite, staurolite, garnet, sillimanite, andalusite, etc. These differences in minerals of course make wide differences in average dimensions of the particles present in the original and sedimentary rock (a difference in addition to the variations in dimensions shown by minerals appearing both in sediments and flow-cleavage rocks). These mineralogical differences have a further effect in determining the nature of the parting. In both sediments and rocks with secondary cleavage it is parallel to the longer dimensions of the particles, but in the former, where quartz and feldspar are dominant, the parting is mainly intermineral, while in the latter mica and hornblende are dominant and the best parting may follow the mineral cleavages, although both kinds of parting may be present in both classes of rocks.

In general it appears that so far as the structure itself is concerned there is no essential difference between potential parting in the bedding of an indurated sediment and that in a metaclase or rock with secondary cleavage. Both are due to differential pressure. Both are molecular phenomena conditioned by the same kinds of factors. However, in origin and in the range of the different factors favoring the parallel parting, the two structures are widely different and should of course be described under two names.

BEDDING IN NONCLASTIC SEDIMENTS.

Excellent bedding may sometimes be observed in nonclastic sediments which may or may not yield a rock cleavage. The most common of the nonclastic sediments—limestone—sometimes shows a good bedding cleavage and sometimes not. When present, it is clear that the bedding cleavage is not due to the parallel arrangement of mineral constituents, but to the intrinsic weakness of certain layers. The subsequent alteration of a nonclastic rock through chemical changes may emphasize the bedding, as by the segregation of limestone and chert in a limestone formation, or the segregation of chert and iron oxide in an iron formation resulting from the alteration of iron carbonate. Where the original bedding has been so emphasized the capacity to part is clearly due to interbanding of materials differing widely in nature, certain layers being weaker than others, or the layers of different character having weak adhesion (Pl. XXV).

FLOW STRUCTURE IN IGNEOUS ROCKS.

An original cleavage is sometimes found to have been induced in igneous rocks prior to or contemporaneous with their solidification from a magma. In the original flow structure of lavas there is a tendency for any unequidimensional crystals to be arranged with their greater diameters parallel to the flowage lines, and there is a marked tendency for minerals of the same kind to be concentrated into layers, both of which phenomena may yield a rock cleavage. The cause of the parallel arrangement of flowage is one which need not here be discussed beyond the general statement that the arrangement is probably due to rotation of random particles during the flowage of the lava, and perhaps also to development in situ under unequal stresses set up during later stages and caused by cooling of the mass. The arrangement of particles is dimensional. Commonly this arrangement is partial rather than complete, but dimensional axes of one kind in the different particles may be parallel, while the others are parallel to a plane and not to one another. A large proportion of minerals in an original rock have crystal shape or habit, and thus present uniform relations of their crystallographic axes to their dimensions, and hence their crystallographic axes are arranged to the same degree as their dimensions. This crystallographic arrangement is found in mica and hornblende, and partially also in feldspar. Pressure effects and breaking and separation of particles in the lines of flow are common.

Certain original gneisses should probably also be described in this connection, although it is believed that the majority of gneisses are the result of secondary metamorphic action and therefore should properly come under the discussion of secondary rock cleavage. The gneisses with original parallel structure are not surface rocks, but in many cases are found in dikes or in other forms whose structural relations show them to have undergone practically no deformation since solidification.[a] Such gneisses can be proved to be igneous in some cases at least, and are probably so in the majority of cases, and if their parallel structure is induced prior to solidification it may be in somewhat the same way that the flowage structure of lavas is induced, although the parallel development of minerals in situ due to differential stresses set up in the rock during the later stages of its cooling may be more important than the rotation of random original particles. There is a dimensional parallel arrangement of the particles of the gneisses, but the minerals possess characteristic crystal shape to a small degree and hence there is little crystallographic parallelism of the mineral particles. Mica and hornblende are the only ones which show crystallographic arrangement. Quartz and feldspar are exceedingly irregular in outline, and their dimensional parallelism would be likely to be overlooked in a hasty examination.

As in the comparison of the original cleavage of sediments and flow cleavage, all of the features above described for the original cleavage

[a] A clear case of the development of an original parallel structure in gneisses is found in the Animas Canyon of southwestern Colorado, where, according to Mr. Whitman Cross, dikes of gneiss have intrusive relations to ancient hornblende-schists. The dikes give no evidence of secondary deformation and presumably the parallel structure of the gneiss is original. The writer is indebted to Mr. Cross for an opportunity to examine specimens from this locality. (Specimens 10, 13, 152, 153, 2937, 2943, 2947, 2948.)

of igneous rocks are duplicated in secondary cleavage, but in varying degree. Indeed, the general aspects of the two are frequently surprisingly similar. This is well shown in the behavior of finer constituents in passing around phenocrysts in both original and secondary rocks. In kinds of minerals represented in the igneous rocks with original cleavage and in rocks with secondary cleavage there are differences. Probably mica and hornblende are relatively more important in the latter than in the former, while quartz and feldspar are relatively more important in the former, although both are present in both kinds of rocks. In shape of particles there are minor differences. Angular fragments due to granulation in the rocks with secondary cleavage probably do not have their counterparts in so great abundance in the original igneous rocks with cleavage. The crystals in the original rock are probably not so unequidimensional on an average as those in rocks with secondary cleavage and probably show differences in size, either larger or smaller, depending on the dominance of the processes of recrystallization or granulation in rock flowage. Differences in the relative dimensions of the greatest and least diameters of the particles in the original and secondary rocks seem to be indicated by measurements. For instance, secondary green hornblende in schists shows an average relation of length to thickness of about 100 : 20. Measurements of the same dimensions of similar hornblendes in unaltered rocks give a ratio of about 100 : 40. The parallel arrangement, even if brought about under the same conditions in the two classes of rocks, would not be expected to be equally uniform in both, and as a matter of observation, it is not, but the arrangement is brought about under different conditions and the cause may not be connected with the dimensions of the particles. The crystallographic properties, therefore, show less tendency to be parallel in the original igneous rocks than in the secondary rocks. The concentration of the hornblendes and micas in layers in the secondary rocks with cleavage affords an excellent parting not attainable in the original igneous rocks where these minerals, if present, are not concentrated to such an extent. The breaking of crystals and their separation in lines of flow are strikingly similar in original and secondary rocks.

It thus appears in the comparison of rocks with secondary cleavage and igneous rocks showing flow structure and cleavage that there is a similarity of phenomena throughout. In both the parting is a molecular phenomenon and thus a true cleavage. But still sufficient and characteristic differences are present to make discrimination possible in some cases. The original cleavage in an igneous rock showing flowage structure is in general far less ready than in either the indurated sediments or in the typical crystalline schists or slates.

MISCELLANEOUS.

There remains to be discussed a variety of original parallel structures, such as pegmatite, perthite, and parallel arrangements, particularly of feldspar crystals, in rocks both basic and acidic, perhaps due to original flowage and perhaps partly pegmatitic in origin. The parallel arrangement of pegmatites and perthites has little similarity with the secondary parallel arrangement incidental to rock flowage. In either case there is no dimensional arrangement of the minerals as a whole with reference to the pressure, but rather an intergrowth of two minerals and uniformity in arrangement only with reference to each other, due to causes not well understood. It is the peculiar control which the physical properties of a mineral sometimes exert on the arrangement of another mineral close at hand. The development of minute crystals of one mineral with different arrangement on the crystal surfaces of another is an illustration of such control. In pegmatites the cleavage is that of the constituent minerals, and may vary in direction from mineral to mineral; in rocks with secondary cleavage it is of the complex nature already described.

The characteristic arrangement of feldspar parallel to its tabular development found in many original basic and acidic rocks presents an interesting analogy with certain schists. This parallel arrangement is found in the banded gabbros of the Adirondacks[a] and northeastern Minnesota, the nepheline-syenites of central Wisconsin,[b] the porphyritic gneiss from the main shaft of the Hoosac tunnel, Massachusetts, and certain other labradorite-porphyrites from America and Europe. An examination of the feldspars of these rocks shows them to be simply twinned parallel to the clinopinacoid or brachypinacoid. In all cases also their tabular development is parallel to this plane, and they lie in the rock with these planes parallel. In some cases, as in the banded gabbro and in the nepheline-syenite, the parallelism goes still farther and the crystallographic axes in this plane are parallel, as shown by the parallelism of the basal cleavages. This arrangement of the feldspars gives the rock in which it occurs a cleavage parallel to the tabular development of the feldspar, and where the basal planes are parallel, a cleavage parallel to them. The rock cleavage so formed is mainly cohesion cleavage, as it follows the brachypinacoidal or basal cleavage of the feldspar. In certain schists a similar secondary arrangement of this kind has been found (pp. 35–37), but in this case the secondary feldspars have not nearly so great differences in dimensions as the original ones, and, furthermore, the rock cleavage is not conditioned by the feldspar mineral cleavage, but the feldspar is associated with mica and the rock cleavage is largely parallel

[a] Sp. 14764, sl. 9399, near Thompson, Minn.; sp. 18242, sls. 9754, 14972, 14973, 14974, Westport, N. Y.

[b] Sps. 5261, 5821, 5823, 5824, 5825, near Wausau, Wis. Cf. Weidman.

to this mineral. The similarity of the development and arrangement in the original and secondary rocks brings to mind the possibility that the original parallel structure may be due to differential pressure. The rocks showing this arrangement have in many cases certainly not undergone mechanical deformation. The parallel arrangement is found in fresh massive gabbro in which the feldspars almost certainly are original. If this arrangement were attained before the complete solidification of the magma, as seems most likely, it could come about either through rotation of unequidimensional particles or through development in situ. If such large feldspars were present in the magma before solidification, the viscous movement prior to cooling would undoubtedly have had a rotating effect on the crystals, and the tendency might be to bring them into dimensional parallelism. The same result might perhaps be attained by the rotation of such crystals under the differential stresses caused by the cooling of the magma. Brögger is strongly of the opinion that the forces in a cooling viscous magma are unequal in different directions; that at any point they may be resolved into three mutually perpendicular differential stresses. In neither case is it clear how a good tridimensional parallelism can result from the rotation of crystals of which two of the three dimensions are not far different. As an alternative the feldspars may be supposed to develop entirely after such differential stresses incidental to cooling have been set up. In this case it is analogous to the development of minerals by recrystallization under conditions of differential pressure in the development of cleavage during rock flowage. This seems to offer a basis for a more reasonable explanation of the excellent parallel, almost pegmatitic, structures observed in many of the original igneous rocks, than rotation of crystals previously formed.

Still another possible arrangement yielding parallel parting should be mentioned. It is conceivable that if in a rock, say a gneiss, the materials of differing strength are concentrated in alternate bands, there might be a tendency to part in parallel planes, even if the individual particles were not arranged. No case of this has appeared during this investigation.

CONCLUSION.

To the cleavage of original rocks, then, such as sedimentary bedding, flow structures in lavas, etc., statements similar to those made concerning secondary cleavage may apply. The cleavage is conditioned by the same factors of dimensional and crystallographic arrangement, although these factors have different ranges. The relations to pressure are probably similar, although observational evidence is partially lacking. The only essential difference is in the processes through which the arrangement is brought about. Pegmatites and perthites present no dimensional arrangement of the minerals, and their cleavage is essentially a local mineral cleavage differing in character from the rock cleavage under discussion in this paper. The cleavage in such rocks is coterminous with the individual minerals and does not extend in the same planes through any great mass of the rock; it is then properly not rock cleavage.

SUPERPOSITION OF SECONDARY FLOW CLEAVAGE ON ORIGINAL CLEAVAGE.

It is evident that secondary flow cleavage can develop in a rock which is either with or without any previous parallel structure, and may have any position relative to such previous parallel structure. If the flow cleavage is developed parallel to the earlier parallel structure, the latter is simply emphasized. If the flow cleavage is developed in planes inclined to the earlier structure, both the original and secondary structures may be present in the earlier stages of the development of the latter. In later stages the earlier parallel structure is necessarily destroyed by the development of the secondary cleavage. The secondary cleavage is conditioned by the dimensional arrangement of the particles, and the longer diameters of the particles in a rock can not be parallel to both original and secondary structures.

Secondary flow cleavage is very commonly developed in sedimentary bedded rocks, and here the original and secondary structure may be frequently recognized. The bedding may be indicated by actual fractures due to readjustment between the beds, by variation in texture of the different beds, or by variation in the mineral content of the different beds, even though all trace of the original parallel arrangement is entirely destroyed. Pl. XIV, *A*, shows a secondary cleavage crossing the bedding of a banded graywacke and slate.[a]

The long dimensions of the individual particles correspond in directions with the secondary cleavage. The original bedding is shown only in the alteration in coarseness and mineralogical character of the bands. In the hand specimen from which this slide is taken the parting is parallel to the secondary cleavage, and, while the original bedding shown by the banding is conspicuous, the parting parallel to it is practically nil.

In the instance cited the secondary parallel minerals developed by recrystallization across the bedding show greatly varying coarseness, and this coarseness corresponds roughly to the texture of the bands which they cross. Where an original bedding layer is coarse, the micas crossing it are in coarse conspicuous flakes; where the texture of the bedding layers is fine the mica crossing it is fine (Pl. XIV, *A*). This serves really to emphasize the original alternation in texture of the

[a] Sps. 14974, Black Hills, South Dakota; 7712, Menominee district of Michigan; 29217, Ocoee area, Tennessee; see also sps. 14858, 14981, 14861, 14862, Black Hills, South Dakota; 14745, Little Falls, Minn.; 25575 and 25584, between Thompson and Livingston, Ga.

For excellent illustrations of cleavage crossing bedding, see Dale's report in Nineteenth Ann. Rept. U. S. Geol. Survey, 1899, pt. 3.

bedding. Thus while original parallel arrangement is completely destroyed by the secondary arrangement, the bedding layers, as shown by alteration of textures, are even more conspicuous than before. It is believed that this correspondence in texture of original and secondary minerals in the early stages of recrystallization is a general phenomenon wherever recrystallization occurs—that is, the finer the original particles the finer the secondary ones developing among them. The micas developing in a slate, for instance, tend to be individually smaller than those developing in a coarser schist.

The attitude of secondary flow cleavage with reference to the major bedding structures in deformed sedimentary rocks has been observed for many years and the general relations of the two are known. As the sedimentary layers of the earth's crust have been originally almost parallel to the surface of the earth, and as the deformation of such rocks has been mainly through circumferential shortening of the outer portion of the lithosphere, it is in accordance with the law that cleavage develops normal to the shortening of the rock mass that cleavage is frequently highly inclined to bedding. However, in the deformation of bedded rocks of heterogeneous character the nature of the deformation must vary from bed to bed and from time to time, with corresponding variations in cleavage. A full discussion of the attitude of cleavage with reference to bedding is not essential to the purposes of this paper and will be omitted. However, there should be mentioned the well-known tendency of cleavage to cut across the harder layers at high angles and to curve toward parallelism with the bedding in the softer layers. This is because of a frequent difference in the nature of the strains in the hard and soft layers. If the strata have been shortened parallel to their own plane the cleavage in general has a tendency to develop normal to the beds; the strain is essentially pure shortening. But in the folding which accompanies shortening there must be readjustment between heterogeneous rocks or within the softer layers of the series. In the softer layers the strain is largely of the kind known as scission. Cleavage developing under scission is rapidly rotated toward the plane of scission, which in the case of the soft layers would be the plane of bedding; hence the frequent tendency of cleavage toward parallelism with the bedding in the softer layers, and the peculiar S curve so characteristic of cleavage in rocks of varying hardness (fig. 37).

SUPERPOSITION OF FRACTURE CLEAVAGE ON ORIGINAL CLEAVAGE.

It is apparent that fracture cleavage may be developed without in any way obliterating original cleavage, and indeed may emphasize it. As in the case of the superposition of a fracture cleavage on a flow cleavage the preexisting cleavage may determine the plane of parting even where this is inclined somewhat to what would be the plane of parting were the rock homogeneous. Thus it is we have common slips along bedding planes and more widely spaced fractures at angles to it. The statements made on pages 130–133 concerning the superposition of a fracture cleavage on flow cleavage will also apply in the main to superposition of fracture cleavage on original cleavage.

One of the results of the superposition of fracture cleavage on original cleavage is the development of "cleavage bands" resulting from the softening of material by shearing along the fracture cleavage, which allows such bands to weather out readily and gives the rock as a whole a conspicuous banding (Pl. XVII, *A*).

PLATES.

PLATE I.

PLATE I.

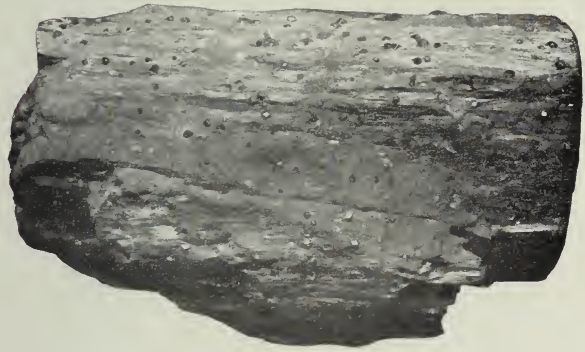
SPECIMENS ILLUSTRATING PLANE-PARALLEL AND LINEAR-PARALLEL TYPES OF FLOW CLEAVAGE.

A.—Micaceous schist with plane-parallel type of cleavage. From Black Hill Specimen No. 14858. The black bands represent bedding, and the cleavag is inclined to the bedding. Under the microscope all the constituents of th rock, mainly mica and quartz, are seen to lie with their greater and mea diameters in the plane of rock cleavage. It is indeed the tridimensional pa allelism of these particles which gives the rock its plane-parallel type c cleavage.

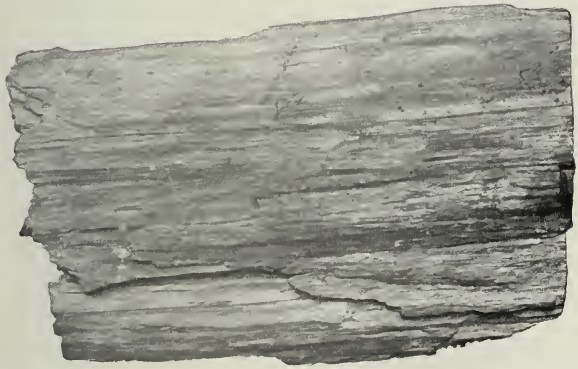
B.—Micaceous schist with linear-parallel type of cleavage. From Black Hills Specimen No. 14943. Under the microscope the constituents of the rock mainly quartz and mica, are seen lying with their longer diameters parallel t a line and not to a plane. The micas are for the most part bent and contorte in all directions but one, the line of cleavage. The garnets have develope subsequent to the development of the cleavage.

C.—Micaceous schist with cleavage intermediate between plane-parallel and linear parallel type. From Black Hills. Specimen No. 14959. The mica plates ar bent and contorted and have the same arrangement on a minute scale as i shown by the rock surface on a larger scale. (See Pl. II, *B*.)

A



B



C

PLANE-PARALLEL AND LINEAR-PARALLEL TYPES OF FLOW CLEAVAGE.

PLATE II.

PLATE II.

PHOTOMICROGRAPHS OF MICACEOUS SCHISTS.

A.—Photomicrograph of micaceous schist from Hoosac tunnel. Specimen No. 18062. With analyzer, x 96. The micas, which are entirely new developments by recrystallization, lie in flat plates with their greater diameters roughly parallel. Each individual exhibits several twinning lamellæ. It will be noted that, while there is apparently a bending and irregularity in the mica plates, the individuals are for the most part not deformed, and the impression of irregularity is caused by the individuals feathering out against one another at low angles. This sort of arrangement is frequently seen about rigid particles which have acted as units during deformation, indicating that the arrangement is due to differing stress conditions at different places. Where the harder minerals are not present it is believed that the feathering out of the mica plates results from changing conditions of stress at different times during the rock deformation, as well as changing conditions of stress at different places in the rock mass (pp. 113–114).

B.—Photomicrograph of micaceous schist. From Hoosac, Mass. Specimen H, 1061.2. With analyzer, x 40. In this rock the mica plates are new developments, but here they have undergone subsequent deformation and bending. The difference between this manner of deviation from parallelism and that shown in *A* is apparent.

A

B

MICACEOUS SCHISTS

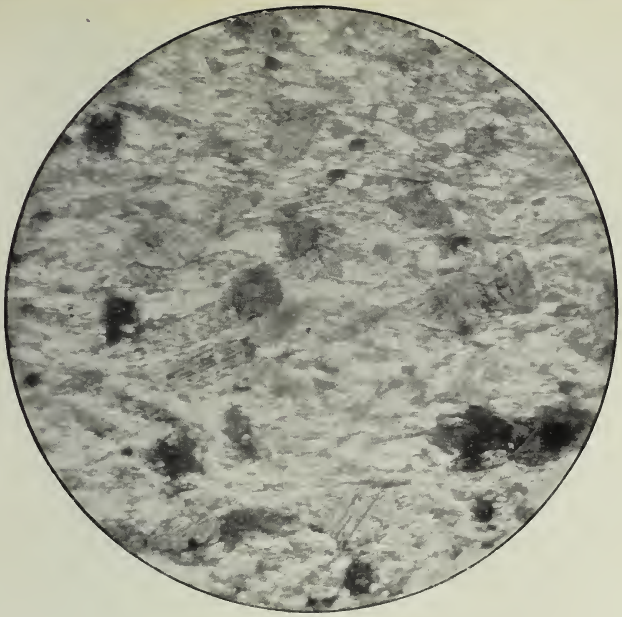
PLATE III.

PLATE III.

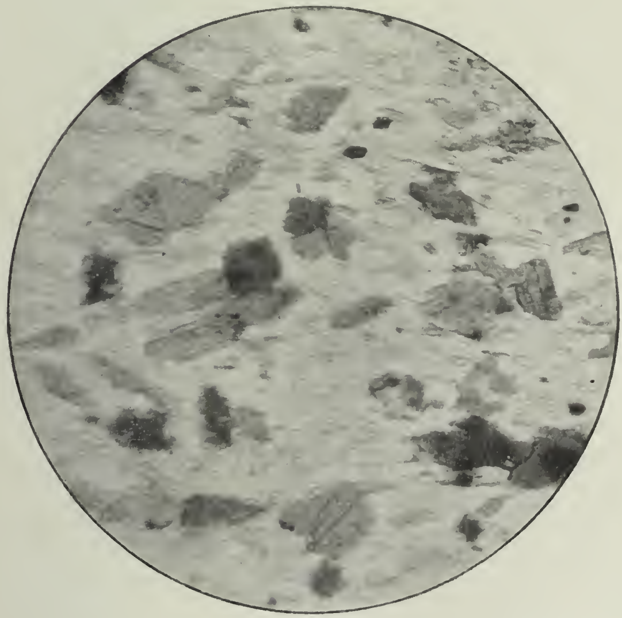
PHOTOMICROGRAPHS OF MICACEOUS SCHIST, SHOWING BIOTITE FLAKES LYING ACROSS THE SCHISTOSITY.

A.—Photomicrograph of a micaceous schist. From Gogebic district of Michigan. Specimen No. 14930. Without analyzer, x 40. Biotite crystals have developed in porphyritic fashion with their greater diameters or cleavage or both lying at various angles to the plane of rock cleavage. The biotites have the same occurrence as minerals such as garnet, chloritoid, tourmaline, etc., which have developed later than the deformation producing the flow cleavage.

B.—The same with analyzer.



A



B

MICACEOUS SCHIST.

Showing biotite flakes lying across the schistosity. *A*, Without analyzer; *B*, with analyzer.

PLATE IV.

SPECIMENS OF HORNBLENDIC SCHISTS, ILLUSTRATING PLANE-PARALLEL AND LINEAR-PARALLEL TYPES OF FLOW CLEAVAGE.

A.—Hornblendic schist with plane-parallel type of cleavage. From Mesabi district of Minnesota. Specimen No. 45379. The hornblende particles in this rock have a tridimensional parallelism, and the rock breaks easily parallel to the greatest and mean diameters, and less easily parallel to the greatest and least diameters.

B.—Hornblendic schist with linear-parallel type of cleavage. From Mesabi district of Minnesota. Specimen No. 40686. The longest diameters of the hornblende crystals lie parallel to one another, but their mean and least diameters are not mutually parallel. The rock accordingly cleaves in any plane parallel to the greatest diameters of the hornblende crystals.

A

B

HORNBLENDIC SCHISTS.

Illustrating plane-parallel and linear-parallel types of flow cleavage.

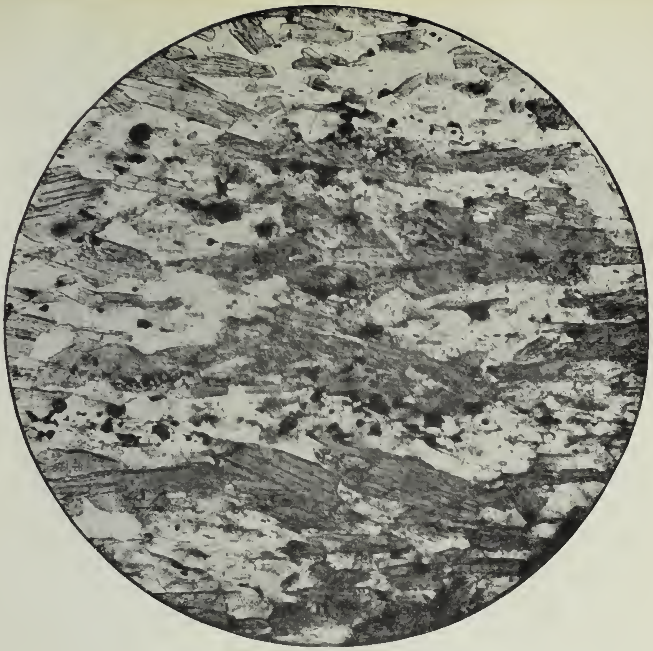
PLATE V.

PLATE V.

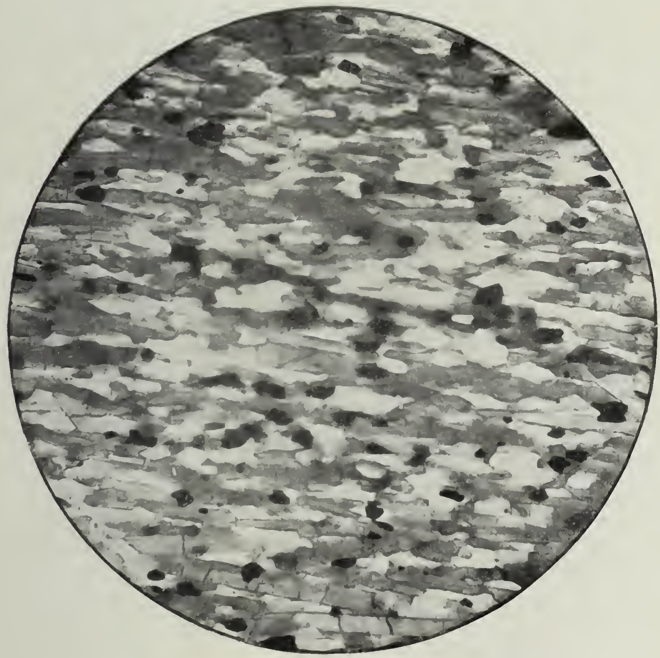
PHOTOMICROGRAPHS OF HORNBLENDIC SCHISTS, SHOWING ARRANGEMENT OF HORNBLENDE CRYSTALS PARALLEL TO COLUMNAR AXES.

A.—Photomicrograph of hornblendic schist from the Vermilion district of Minnesota. Specimen No. 28502. Without analyzer, x 75. While there are numerous minor irregularities, the general parallelism of the longer axes of the hornblende crystals is apparent.

B.—Photomicrograph of hornblendic schist from Menominee district, Michigan. Specimen No. 26148. Without analyzer, x 75. The parallelism of the green hornblende crystals is more marked than in fig. 1.



A



B

HORNBLENDIC SCHISTS.

Showing arrangement of hornblende crystals parallel to columnar axes.

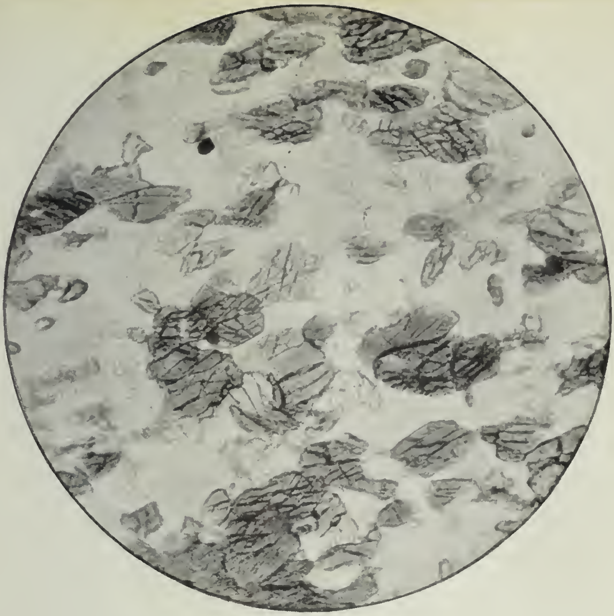
PLATE VI.

PLATE VI.

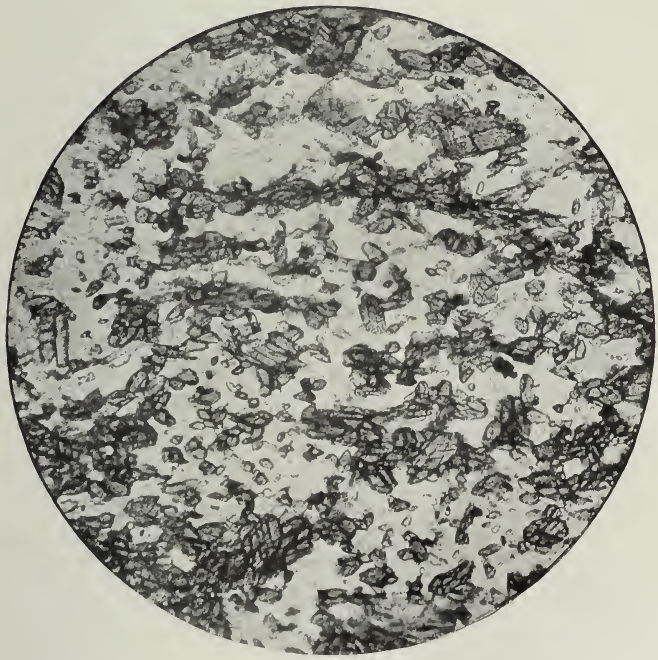
PHOTOMICROGRAPHS OF HORNBLENDIC SCHISTS, SHOWING THE ARRANGEMENT OF HORNBLENDE CLEAVAGE IN SLIDES CUT ACROSS THE SCHISTOSITY.

A.—Photomicrograph of hornblendic schist from Mesabi district of Minnesota. Specimen No. 45416. Without analyzer, x 75. The basal hornblende sections at first glance seem to have no orderly arrangement, but on examination it is seen that the acute angles of the prismatic cleavage have a slight tendency to parallelism.

B.—Photomicrograph of hornblendic schist from Vermilion district of Minnesota. Specimen No. 28501. Without analyzer, x 90. The acute angles of the prismatic cleavage of the hornblende have a faint tendency to lie in the same plane. This is scarcely apparent from the photomicrograph, but an examination of the slide itself leaves no doubt of its presence.



A



B

HORNBLENDIC SCHISTS.

Showing arrangement of hornblende cleavage in slides cut across the schistosity.

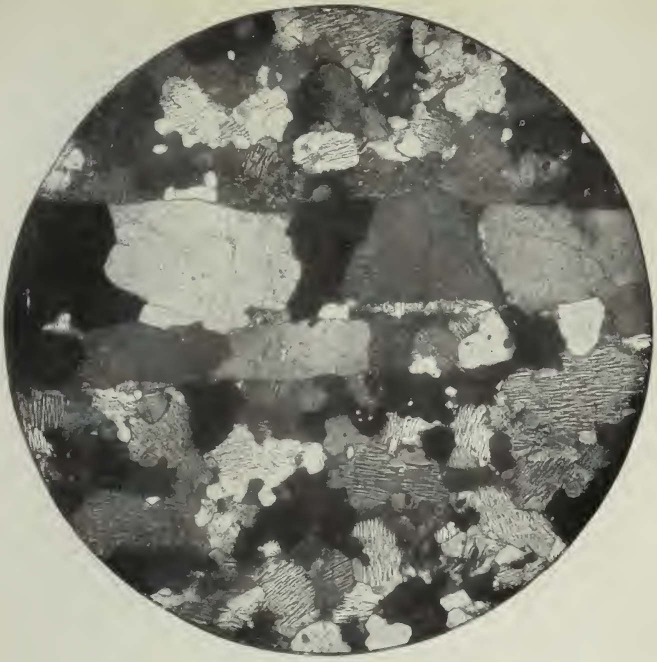
PLATE VII

PLATE VII.

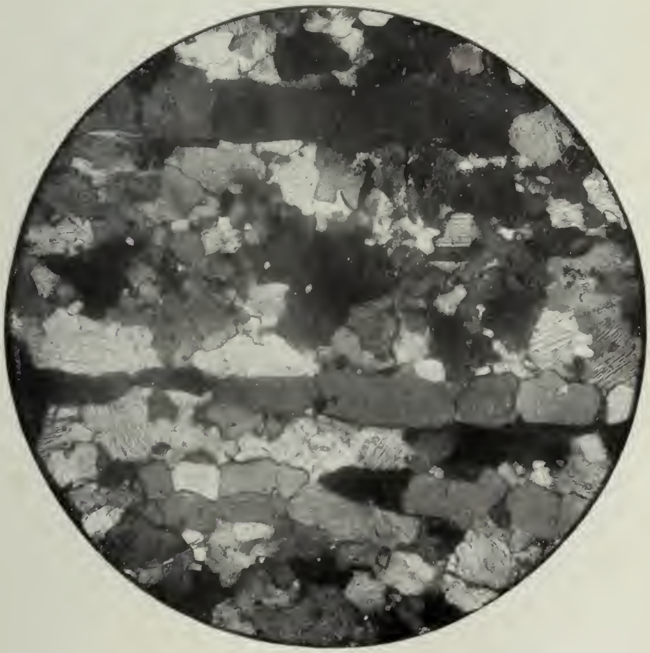
PHOTOMICROGRAPHS OF LEAF GNEISS.

A.—Photomicrograph of leaf gneiss from the Laurentian area north of Montreal. Slides furnished by Frank D. Adams. With analyzer, x 60. Doctor Adams has described the leaf gneiss as resulting from granulation of a hornblende granite, all stages of the process having been noted. (See Part J of Vol. VIII of the Geological Survey of Canada, 1895.) The striated feldspars have irregular angular shapes such as characteristically result from granulation. The two bands of quartz crossing the slide evidently owe their form and arrangement finally to recrystallization, although granulation may have been an important initial process. The evidence for recrystallization is stated on pages 82–87. It will be noted that the quartz individuals have dimensional, but not crystallographic parallelism.

B.—The same; another view.



A



B

LEAF GNEISS.

Two views of the same specimen. After Adams.

PLATE VIII.

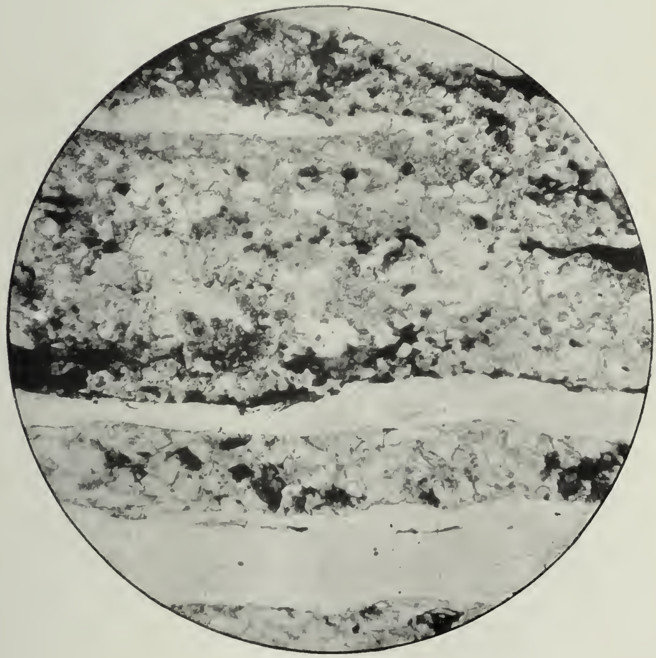
PLATE VIII.

PHOTOMICROGRAPHS OF MICACEOUS AND QUARTZOSE SCHIST.

A.—Photomicrograph of micaceous and quartzose schist from near Westport, N. Y. Specimen No. 18259. With analyzer, x 25. The background is composed of quartz and feldspar, with a considerable amount of chlorite, magnetite, and other accessory minerals. The quartz and feldspar have irregular angular forms such as ordinarily result from granulation. They are similar in their form to the granulated feldspar particles shown in Pl. VII. The bands crossing the slide are quartz and have the same characters as the quartz bands shown in Pl. VII. Granulation probably has aided in the development of the quartz bands, but their final configuration is probably due to recrystallization. It will be noted that the quartz has dimensional but not crystallographic parallelism.

B.—The same without analyzer.

A



B

MICACEOUS AND QUARTZOSE SCHIST.

A. With analyzer; *B*, without analyzer.

PLATE IX.

PLATE IX.

PHOTOMICROGRAPHS OF MICACEOUS AND QUARTZOSE SCHIST.

A.—Photomicrograph of micaceous and quartzose schist from Hoosac, Mass. Specimen H. 1061.3. With analyzer, x 60. The mica is clearly secondary and a result of recrystallization. The quartz is in clear limpid grains with their longer diameters nearly in a common direction. The grains are closely fitting, in bands, and strain effects are lacking, and these facts, together with the association with recrystallized mica, go to show that the quartz has itself been recrystallized. It will be noted that the quartz has no crystallographic parallelism.

B.—The same, with higher power, x 110. The view illustrates in detail the relation of recrystallized quartz grains to recrystallized mica flakes. The mica flakes for the most part separate different quartz individuals, but they may be seen to bound two or more individuals and to project well into them. It is not probable that such a relation could be brought about by granulation, slicing, or gliding, and it seems best explained by recrystallization.

A

B

MICACEOUS AND QUARTZOSE SCHIST.

Same specimen with different powers of analyzer.

PLATE X.

PLATE X.

PHOTOMICROGRAPHS OF MICACEOUS AND QUARTZOSE SCHIST.

A.—Photomicrograph of micaceous and quartzose schist from Hoosac Tunnel. Specimen No. 18062. With analyzer, x 40. The mica is clearly a secondary development by recrystallization, and the quartz in the clear bands has been as certainly recrystallized, as shown by criteria discussed on pages 82–87.

B.—The same, without analyzer; another view.

A

B

MICACEOUS AND QUARTZOSE SCHIST.

A, With analyzer; *B*, without analyzer.

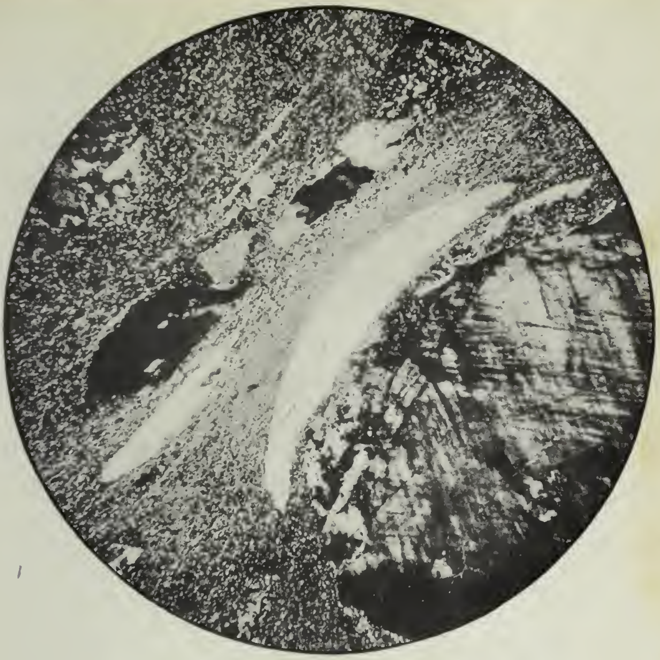
PLATE XI.

PLATE XI.

PHOTOMICROGRAPHS ILLUSTRATING RECRYSTALLIZATION OF QUARTZ AND SLICING OF FELDSPAR.

A.—Photomicrograph of recrystallized quartz from Thüringer Wald. After Futterer (fig. 1, Pl. II, of Ganggranite von Grosssachsen und die Quartzporphyre von Thal in Thüringer Wald: Mitt. Grossh. Badischen geol. Landesanstalt, vol. 2, Heidelberg, 1890). The white area represents recrystallized quartz drawn out about the periphery of a feldspar phenocryst, which has remained unaffected by recrystallization.

B.—Photomicrograph of schistose quartz-porphyry showing sliced feldspar phenocryst in planes inclined to the prevailing cleavage. After Futterer (ibid., fig. 2, Pl. III.).



A. RECRYSTALLIZED QUARTZ.

After Futterer.

B. SLICED FELDSPAR.

After Futterer.

PLATE XII.

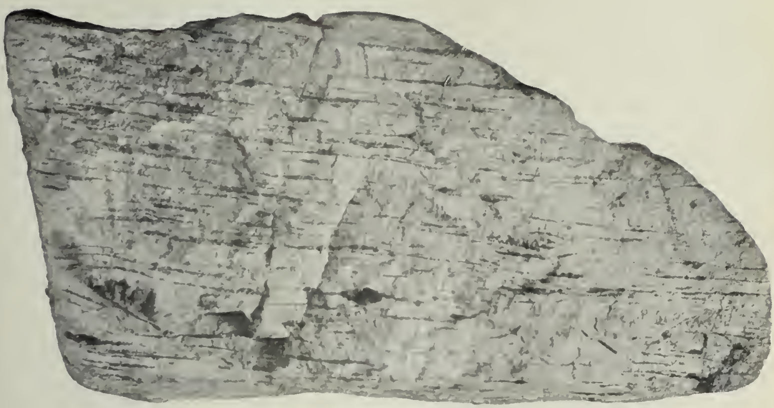
PLATE XII.

SPECIMENS ILLUSTRATING GRANULATION AND SLICING OF FELDSPAR CRYSTALS.

A.—Rhyolite-gneiss from Berlin, Wis. After Weidman (Pl. V of Bull. III, Wis. Geol. and Nat. Hist. Survey, 1898). The feldspar crystals have been crushed and strewn out by granulation and slicing. Minute granules may be seen in various stages of separation from the feldspars, and the larger feldspars may be seen in stages of breaking into slices with their longer diameters inclined to the prevalent cleavage of the rock mass.

B.—Schistose anorthosite from north of Montreal. After Adams (described in Part J of Vol. VIII, Geol. Survey of Canada, 1895). The feldspars and pyroxenes have been granulated and sliced and strewn out in the plane of rock cleavage. The granulation along the sides has left the residual feldspar particles in irregular lens-shaped individuals with their longer diameters parallel to the rock cleavage. Occasionally they are sliced by parallel fractures inclined to the plane of rock cleavage.

A



B

GRANULATION AND SLICING OF FELDSPAR CRYSTALS.

A, After Weidman; *B*, after Adams.

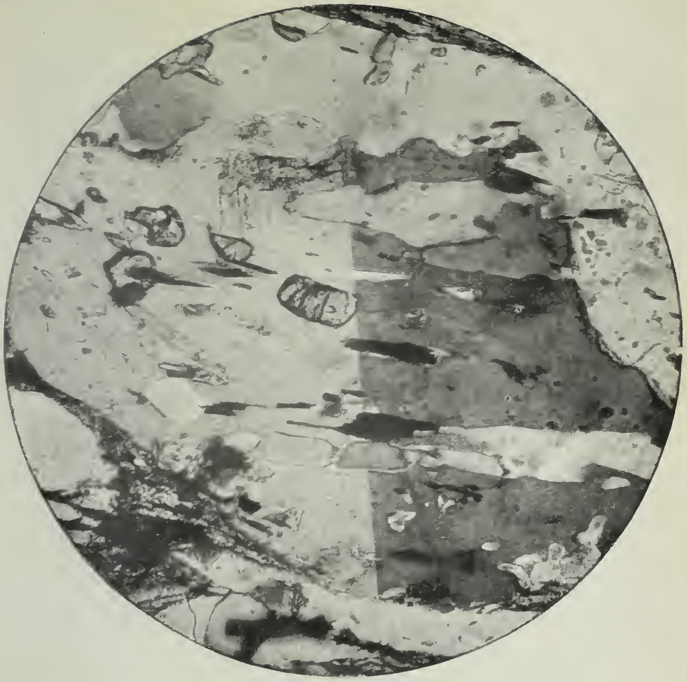
PLATE XIII.

PLATE XIII.

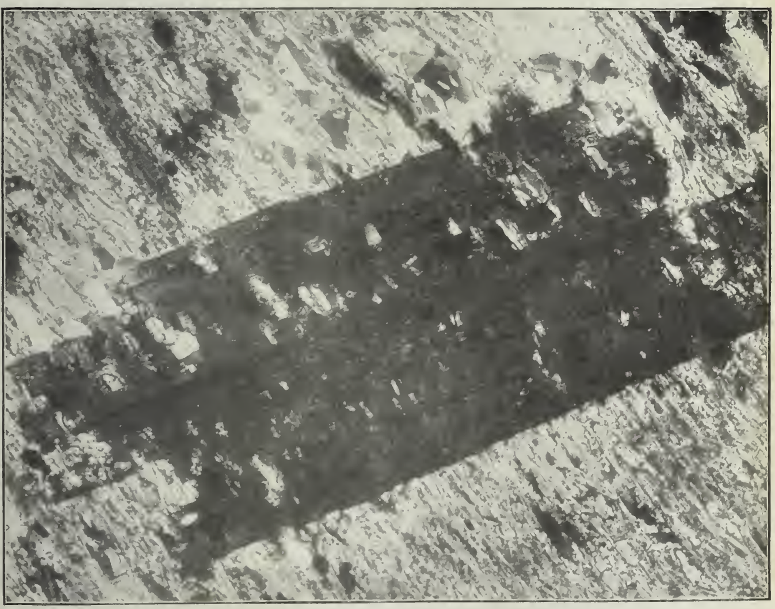
PHOTOMICROGRAPHS OF PORPHYRITIC CONSTITUENTS DEVELOPED AFTER ROCK FLOWAGE HAS CEASED.

A.—Photomicrograph of albite crystal in micaceous and quartzose schist, from Hoosac Tunnel. Specimen 18062. With analyzer, x 67. The field is occupied mainly by one large twinned albite. The numerous inclusions of quartz, mica, and other minerals to be observed in the feldspar have their longer diameters roughly parallel one to the other and to the prevailing cleavage in the rock mass. The albite crystal is supposed to have developed by recrystallization after rock flowage has ceased, using all the constituents necessary for its own growth and leaving the superfluous constituents as inclusions with their orderly arrangement unaffected.

B.—Photomicrograph of chloritoid crystal in micaceous and quartzose schist, from Black Hills. Specimen 14928. With analyzer, x 110. The chloritoid crystal here shown has developed later than the rock flowage producing the prevailing cleavage of the rock. The chloritoid has grown at the expense of the other constituents of the rock, using all the material necessary for its growth and leaving the excess of material in the form of inclusions, which retain their dimensional parallelism with the prevailing rock cleavage.



A



B

PORPHYRITIC CONSTITUENTS DEVELOPED AFTER ROCK FLOWAGE HAS CEASED.

A, Albite crystal; *B*, chloritoid crystal.

PLATE XIV.

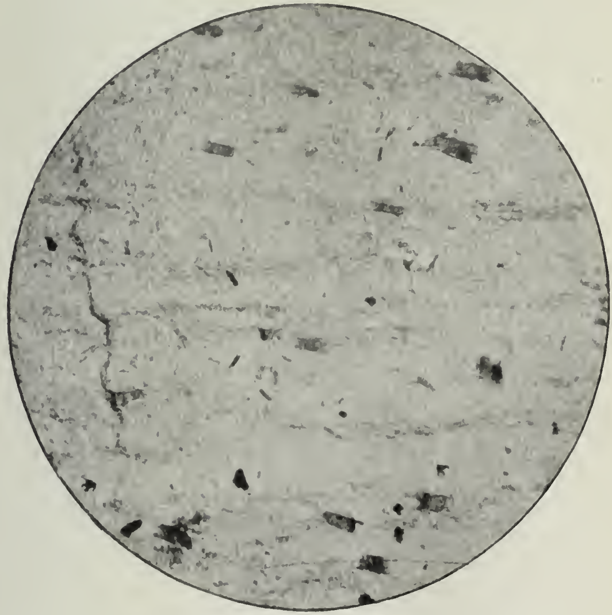
PLATE XIV.

PHOTOMICROGRAPH OF MICACEOUS AND QUARTZOSE SCHIST WITH CLEAVAGE ACROSS BEDDING, AND PHOTOMICROGRAPH OF SLATE WITH FALSE CLEAVAGE.

A.—Photomicrograph of micaceous and quartzose schist with cleavage developed across original bedding, from Little Falls, Minn. Specimen 14745. With analyzer, x 60. A graywacke-slate, in which the banding has been marked by difference in texture as well as in composition, has been subjected to deformation, with the result that a cleavage has been superposed upon the original bedding at right angles to it. Originally the longer diameters of the particles of the bedded rock were parallel to the bedding. Accompanying the development of flow cleavage most of the constituents of the rock have been recrystallized. The quartz particles shown in the light band have been drawn out with their longer diameters nearly at right angles to the former plane of their longer diameters, and abundant new mica has developed with its greater diameters and mineral cleavage normal to the plane of bedding.

B.—Photomicrograph of slate with "false" cleavage, from Black Hills of South Dakota. Specimen 14974. Without analyzer, x 60. The longer diameters of the particles, mainly mica, quartz, and feldspar, lie, for the most part, in a plane intersecting the plane of the page and parallel to its longer sides, but in well-separated planes at right angles to this plane the longer diameters of the particles have been deflected into minute monoclinal folds represented by the darker cross lines. In these cross planes also porphyritic biotites have developed with their longer diameters parallel. The rock has two cleavages, one conditioned by the prevailing dimensional arrangement of the minute particles and the other conditioned by the planes of weakness along the axes of the minute monoclinal folds crossing the prevailing cleavage. The first cleavage is flow cleavage developed in normal fashion during rock flowage, and the second is of the nature of fracture cleavage developed later along separated shearing planes in the zone of fracture or in the zone of combined fracture and flowage. The rock cleaves into parallelopiped blocks.

A. MICACEOUS AND QUARTZOSE SCHIST WITH CLEAVAGE ACROSS BEDDING.



B. SLATE WITH FALSE CLEAVAGE.

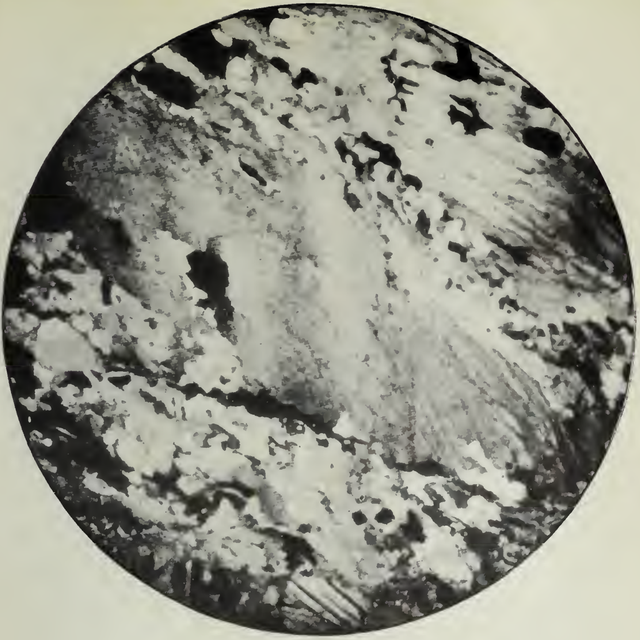
PLATE XV.

PLATE XV.

PHOTOMICROGRAPHS OF ARTIFICIALLY DEFORMED MARBLE (AFTER ADAMS).

A.—Photomicrograph of Laurentian marble which has undergone granulation. After Adams and Nicolson (fig. 3, Pl. XXV, of vol. 195, Philos. Trans. Royal Soc. of London). With analyzer, x 47. Large crystals of calcite have been minutely granulated along their peripheries and the crystals themselves have been twisted and twinned as shown by their minute reedy striations.

B.—Photomicrograph of Carrara marble deformed artificially. After F. D. Adams and J. T. Nicolson (ibid., fig. 4 of Pl. XXIV). With analyzer, x 150. The marble was confined on all sides, was subjected to high temperature, and deformed by a piston. The rock flowed without losing its integrity. The flow took place by the processes of granulation and gliding. The calcite individuals changed their shape and were distinctly elongated without conspicuous fracture, but developed a reedy or fibrous structure, indicating their elongation by gliding along crystallographic planes.



A

B

ARTIFICIALLY DEFORMED MARBLE.

After Adams and Nicolson.

PLATE XVI.

PLATE XVI.

SCHISTOSE MARBLE.

Photograph of schistose marble from Talledega Mountain, Georgia. Specimen 25874. The rock is made up of minute granules of calcite showing dimensional parallelism, as illustrated by fig. 19, p. 41. There is no parallelism of the crystallographic properties of the calcite particles. The parting is determined by the plane of the greatest and mean axes of the parallel arranged granules.

SCHISTOSE MARBLE.

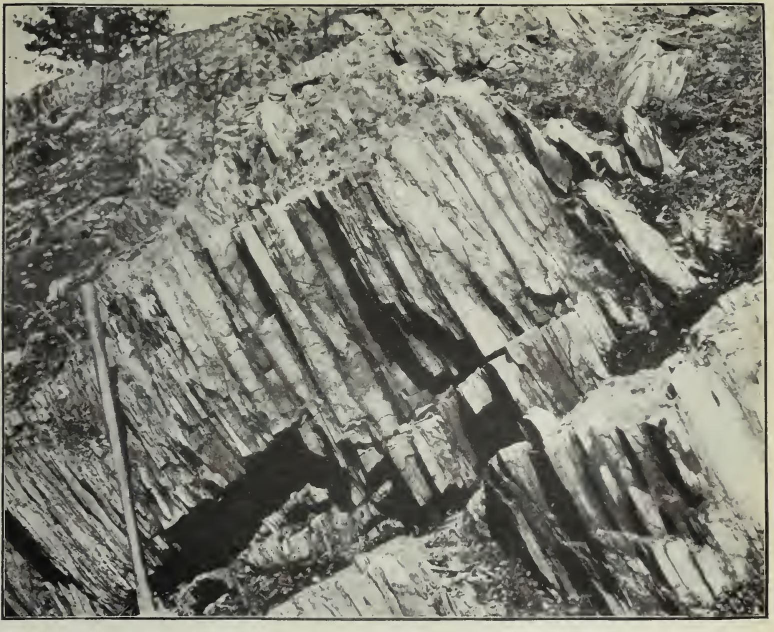
PLATE XVII.

PLATE XVII.

CLEAVAGE BANDS IN ORDOVICIAN SLATES AND PARALLEL QUARTZ VEINS IN CAMBRIAN SLATE.

A.—Cleavage bands in Ordovician slate, from Rupert, Vt. After Dale (fig. B of Pl. XXX, of pt. 3 of the Nineteenth Ann. Rept. U. S. Geol. Survey). The material of this rock was originally nearly homogeneous, and the original bedding crosses the cleavage bands. The softer bands which have been eroded out are described by Dale as zones along which slip cleavage (here called fracture cleavage) has developed. The characteristic occurrence of the slip or fracture cleavage in well separated planes is to be noted.

B.—Parallel quartz veins in Cambrian slate, from Hampton, N. Y. After Dale (fig. A, of Pl. XXXII, of pt. 3 of the Nineteenth Ann. Rept. U. S. Geol. Survey). The veins represent planes of parting along the flow cleavage which by their cementation have yielded what is here called fracture cleavage.



A. CLEAVAGE BANDS IN ORDOVICIAN SLATES.

After Dale.

B. PARALLEL QUARTZ VEINS IN CAMBRIAN SLATE.

After Dale.

PLATE XVIII.

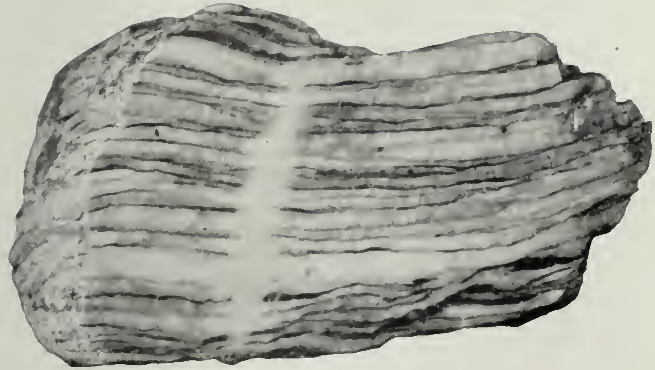
PLATE XVIII.

SPECIMENS ILLUSTRATING FRACTURE CLEAVAGE.

A.—Fracture cleavage developed by the cementation of fissility openings. From Great Basin, furnished by G. K. Gilbert. Specimen No. 42633. The rock has been separated into a series of parallel slices and has been subsequently cemented by the infiltration of calcite. The rock now has a capacity to part, or fracture cleavage, parallel to the calcite veins.

B.—Fracture cleavage in schistose marble. Southern Appalachians. Specimen No. S. 2. Each of the bends is made up of one or few calcite individuals with dimensional but not crystallographic parallelism. It will be noted that the individual bends commonly narrow and feather out. The intervening dark material is chlorite and mica, developed along planes of slipping. The closeness of the planes of parting is rather exceptional. It is to be noted, however, that they are definite in number and separated by zones of distinctly noncleavable material.

A



B

ILLUSTRATIONS OF FRACTURE CLEAVAGE.

PLATE XIX.

PLATE XIX.

SPECIMENS ILLUSTRATING FRACTURE CLEAVAGE.

A.—Fracture cleavage developed by the cementation of fissility openings. From the Vermilion district of Minnesota. Specimen No. S. 14. This is from an Archean jasper formation which has been much broken by fracturing. The closely-spaced parallel fractures in three sets have been cemented by the infiltration of quartz and now remain as potential planes of parting.

B.—Fracture cleavage developed by the cementation of fissility openings. From the Vermilion district of Minnesota. Specimen No. S. 9. Fracturing has occurred along one set of planes, followed by the infiltration of quartz. The rock has then been fractured and faulted again in planes crossing the first formed fractures and these fractures in turn cemented.

A

B

ILLUSTRATIONS OF FRACTURE CLEAVAGE.

PLATE XX.

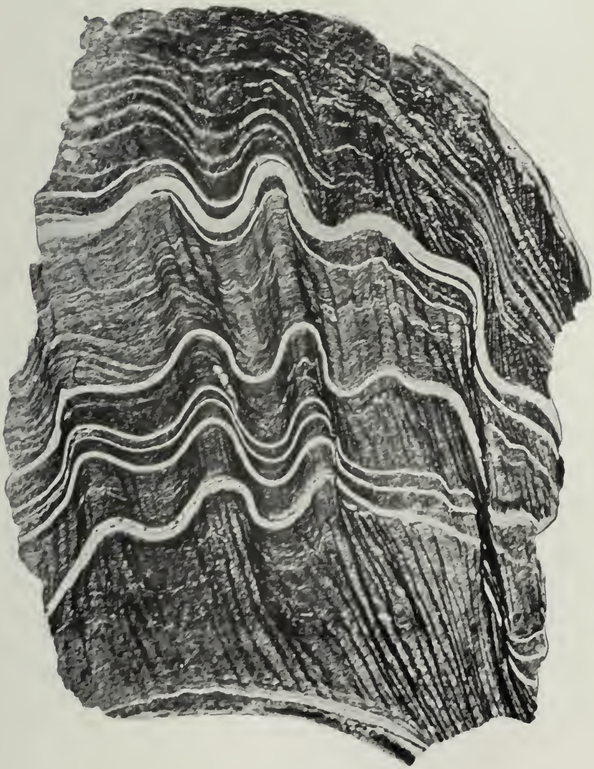
PLATE XX.

SPECIMENS ILLUSTRATING FRACTURE CLEAVAGE.

A.—Fault-slip cleavage in gneiss from southern Appalachians. Specimen No. 25602. The gneiss has been closely crenulated and the minute folds may be observed to pass into minute faults which now represent planes of fracture cleavage. The faults may have been cemented or may have been welded by actual pressure. Parallel to the faults there has also been developed a parallel arrangement of the mineral particles, perhaps due in part to the slipping along the fault planes, and it is exceedingly difficult to distinguish between the fracture cleavage and the flow cleavage.

B.—Schist from Taconic Range, showing minor folding grading into fault-slip cleavage. After Dale (Pl. XIV, *B*, Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 3).

A



B

ILLUSTRATIONS OF FRACTURE CLEAVAGE.

After Dale.

PLATE XXI.

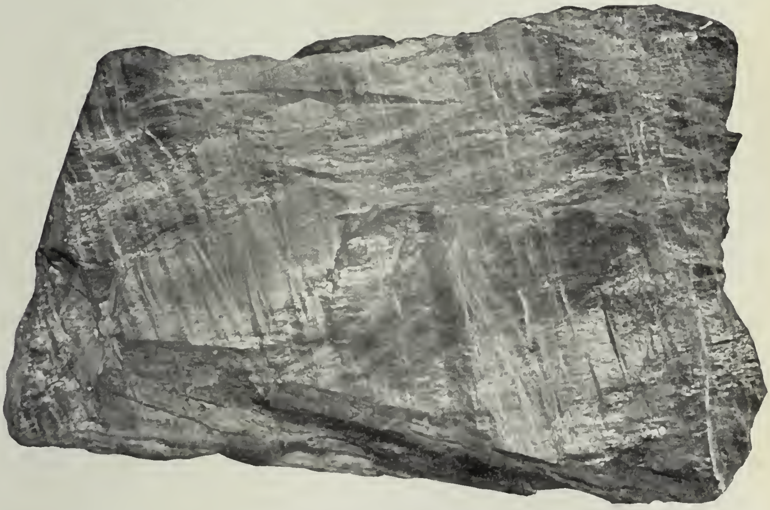
PLATE XXI.

SPECIMENS ILLUSTRATING FRACTURE CLEAVAGE.

A.—Fault-slip cleavage developed in schist. From Marquette district of Michigan. Specimen No. 42617. The schist has been closely crenulated and minute folds may be seen to pass into faults. The rock cleaves parallel to the prevailing schistosity, marked by the longer diameters of the particles; it also cleaves parallel to the limbs of the minute crenulations and parallel to the faults. So far as the cleavage is parallel to the faults, it may be said to be fracture cleavage; so far as it is parallel to the longer diameters of the particles on the longer limbs of the minute folds parallel to the faults, it may be said to be flow cleavage, conditioned by minor bends in the prevalent parallel arrangement of the mineral particles. The rock then shows a fracture cleavage grading into a "false" cleavage along minute folds, both superposed upon an earlier cleavage marked by the prevalent schistosity of the rock mass (pp. 132–133).

B.—"Micaceous hematite." From the Lake Superior region. Specimen No. 25730. Parallel hematite flakes give the prevailing cleavage to the rock. Minute crenulations in this parallel arrangement afford planes of weakness which favor cross breaking. The term false cleavage has been applied to such a cross structure (pp. 25–26, 132–133).

A. FAULT-SLIP CLEAVAGE.



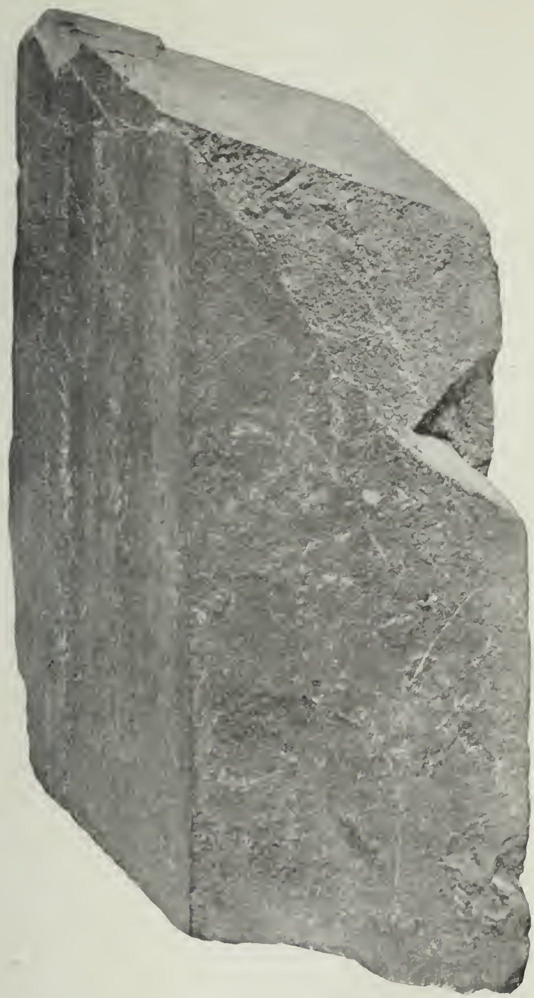
B. FALSE CLEAVAGE.

PLATE XXII.

PLATE XXII.

SPECIMEN SHOWING BOTH FLOW CLEAVAGE AND FRACTURE CLEAVAGE IN THE SAME BLOCK.

Slate from Somerville, Mass. The flat upper surface represents a plane of parting along flow cleavage parallel to the longer diameters of the constituent particles, and the ends and sides of the block represent parting along fracture cleavage independent of any parallel arrangement in the block. The block will cleave into smaller blocks of similar shapes.



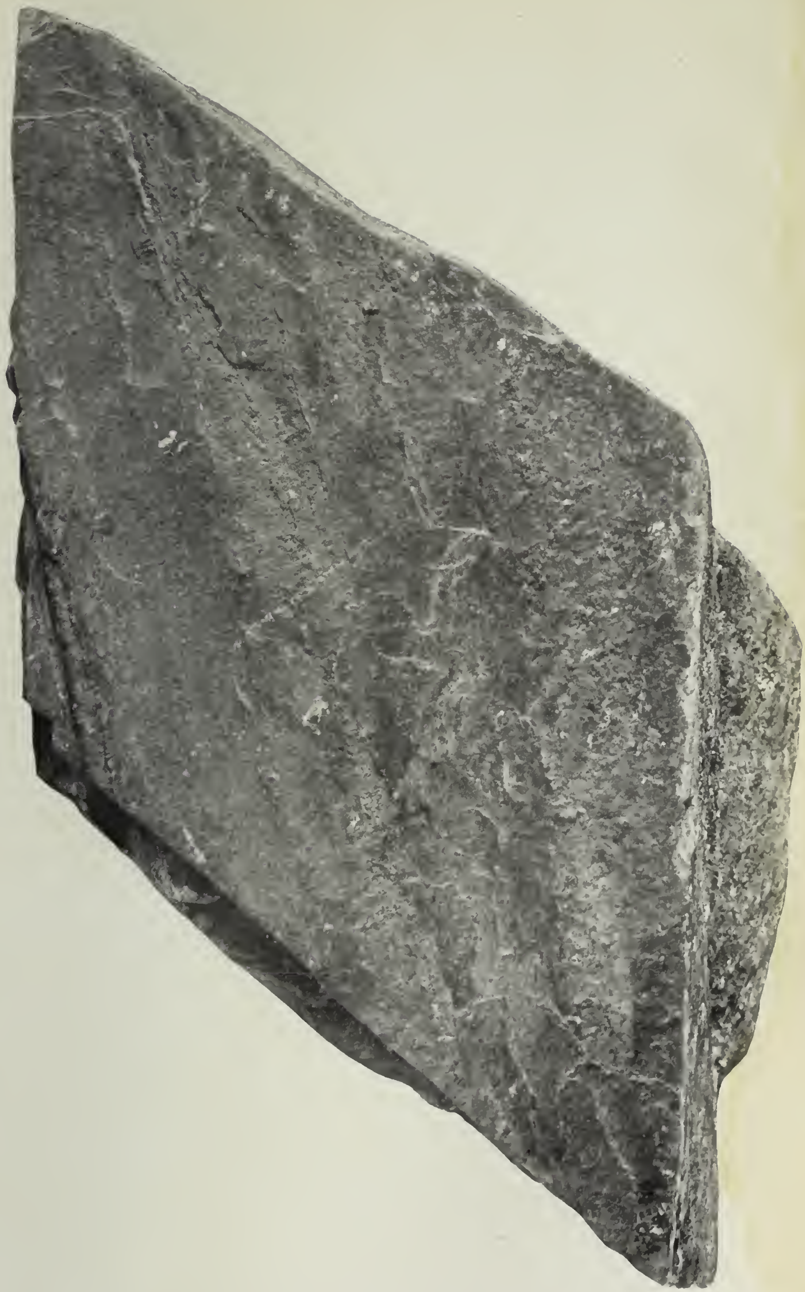
FLOW CLEAVAGE AND FRACTURE CLEAVAGE IN THE SAME BLOCK.

PLATE XXIII.

PLATE XXIII.

SPECIMEN SHOWING BOTH FLOW CLEAVAGE AND FRACTURE CLEAVAGE IN THE SAME BLOCK.

Block of green schist showing both flow cleavage and fracture cleavage. From Menominee district of Michigan. Specimen No. 25664. The flat upper surface (the plane of the page) represents a plane of parting along flow cleavage parallel to the longer diameters of the constituent particles, and the ends and sides of the block represent parting along fracture cleavage independent of any parallel arrangement in the block. The block will cleave into smaller blocks of similar shapes.



FLOW CLEAVAGE AND FRACTURE CLEAVAGE IN THE SAME BLOCK.

PLATE XXIV.

PLATE XXIV.

SPECIMENS ILLUSTRATING PARALLEL ARRANGEMENT OF FELDSPARS IN ROCK MASSES WHICH HAVE NOT UNDERGONE SECONDARY ROCK FLOWAGE.

A.—Gabbro from Westport, N. Y. Specimen No. 18242. The feldspars have tabular development parallel to the brachypinacoid, and lie in the rock not only with their tabular brachypinacoidal faces parallel, but with their basal cleavage faces parallel, as shown by the reflections of the basal cleavage faces. The feldspars are for the most part twinned parallel to the brachypinacoid, and the twinning plane thus bisects the basal cleavage plane parallel to its longest axis.

B.—Nepheline-syenite from central Wisconsin. After Weidman. (Bull. Wis. Geol. and Nat. Hist. Survey, in preparation.) The light colored protruding ridges represent feldspar crystals with an arrangement almost identical with that described for *A.*

A

B

PARALLEL ARRANGEMENT OF FELDSPARS IN ROCK MASSES WHICH HAVE NOT UNDERGONE SECONDARY ROCK FLOWAGE.

After Weidman.

PLATE XXV.

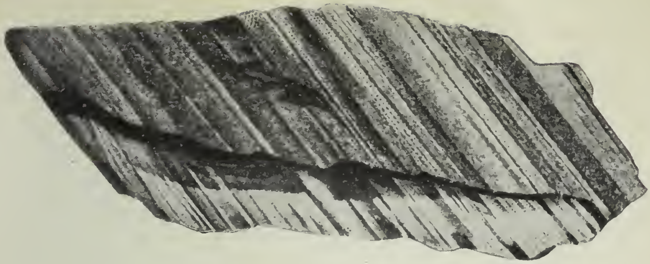
PLATE XXV.

CHEMICAL SEDIMENTS WITH CLEAVAGE.

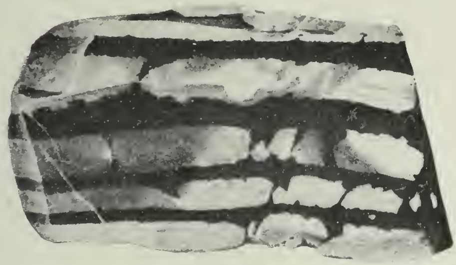
A.—Cherty iron carbonate showing bedding. From Marquette district, Michigan. After Van Hise. (Fig. 2, Mon. U. S. Geol. Survey, vol. 28.) The iron carbonates show a very fine bedding, parallel to which there is a capacity to cleave.

B.—Ferruginous chert resulting from the alteration of iron carbonate with bedding much emphasized by the alteration. From Marquette district, Michigan. After Van Hise. (Fig. 1 of Pl. XX, Mon. U. S. Geol. Survey, vol. 28.) The alteration of the iron carbonates of the Lake Superior region characteristically produces ferruginous cherts and jaspilites in which the constituents are segregated into bands, strongly marking and emphasizing the original bedding. The banding gives a capacity to part along parallel planes, which is truly a cleavage.

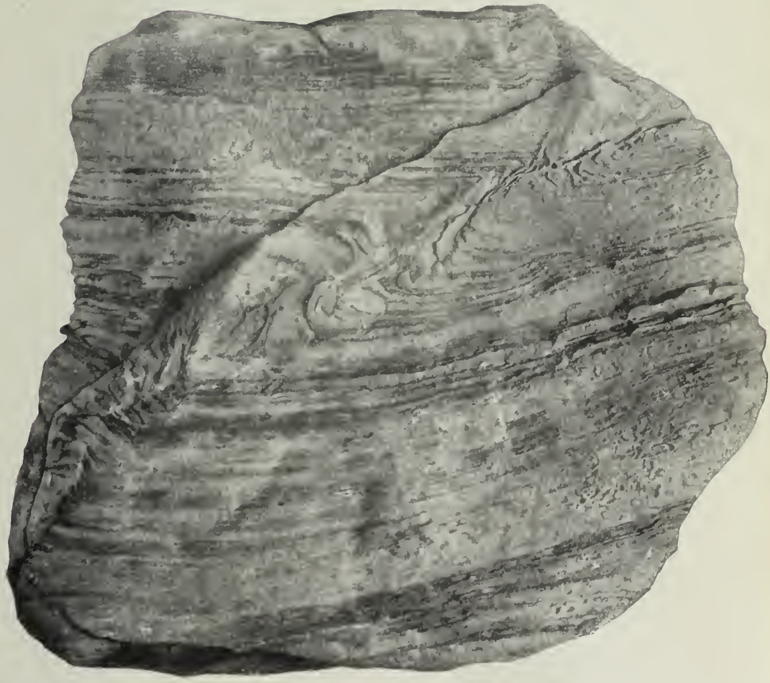
C.—Cherty limestone with bedding marked by minute bands of chert. From north shore of Lake Huron. The segregation of the chert in bands is believed to be largely secondary. The rock possesses a capacity to part parallel to the bands, although the tendency is but a slight one. The fold passing into a fault illustrated in the photograph is a result of later deformation.



A



B



C

CHEMICAL SEDIMENTS WITH CLEAVAGE.

A and *B*, After Van Hise.

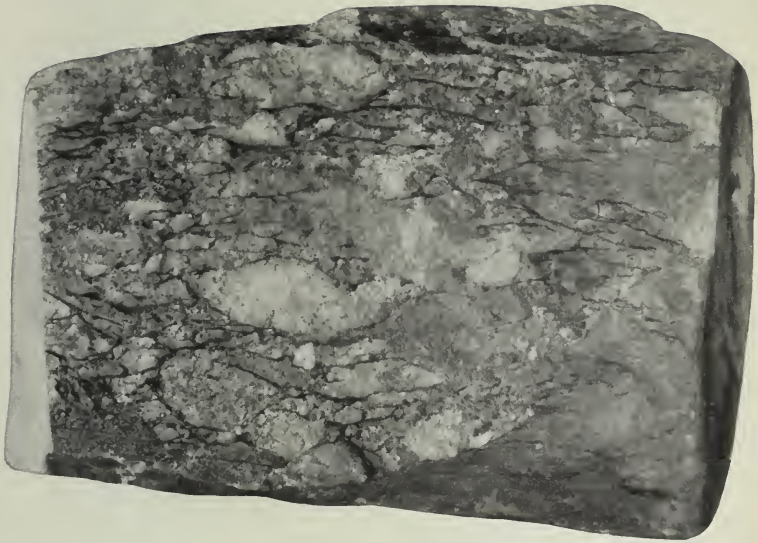
PLATE XXVI.

PLATE XXVI.

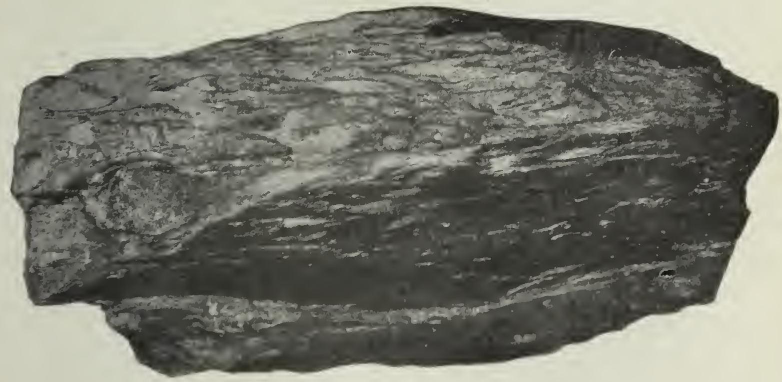
SPECIMEN SHOWING ELONGATION OF PEBBLES IN THE PLANE OF ROCK CLEAVAGE.

A.—Schist-conglomerate. From Black Hills, South Dakota. Specimen No. 14818. The longer diameters of the quartzite pebbles may be seen to lie parallel. This is due to the compression which the rock has undergone.

B.—Same, on opposite side of specimen. This side of the specimen has been compressed so closely and the pebbles so extremely elongated that they are almost indistinguishable. The parallelism of the cleavage with the longer diameters is marked. The rock cleavage follows not only the longer diameters of the elongated pebbles, but occurs within the pebbles themselves parallel to the elongated diameters.



A



B

ELONGATION OF PEBBLES IN PLANE OF ROCK CLEAVAGE.

PLATE XXVII.

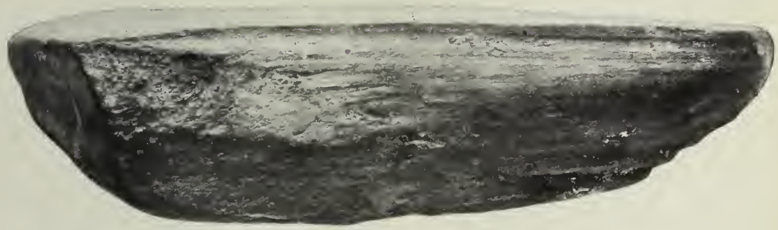
PLATE XXVII.

SPECIMENS SHOWING UNDISTORTED PEBBLE AND PEBBLES ELONGATED IN THE PLANE OF ROCK CLEAVAGE.

A.—Greenstone pebble, undistorted, from pre-Cambrian conglomerate. Pine River, Wisconsin. Specimen No. 45810.

B, *C*.—Distorted pebbles, from pre-Cambrian conglomerate. Pine River, Wisconsin. Specimen No. 45810. The flattening of the pebbles was accompanied by development of an excellent cleavage in the matrix parallel to the longer diameters of the pebbles. The weathering out of this matrix has made it possible to recover the elongated pebble in this condition. The pebbles themselves have their mineral constituents elongated in the same directions, and the pebbles, as well as the matrix, cleave readily parallel to their longer dimensions. There is no possibility that the cleavage of the pebbles was present before the conglomerate was deformed, for in this case the cleavage of all the pebbles would not be so strictly parallel to each other and to the cleavage of the matrix. In *B* the flatness and cleavage of the specimen are normal to the plane of the page. In *C* the flatness and cleavage are parallel to the plane of the page.

A. UNDISTORTED PEBBLE.



B. PEBBLE ELONGATED IN PLANE OF ROCK CLEAVAGE.

C. PEBBLE ELONGATED IN PLANE OF ROCK CLEAVAGE.

INDEX.

O

PUBLICATIONS OF UNITED STATES GEOLOGICAL SURVEY.

[Bulletin No. 239.]

The serial publications of the United States Geological Survey consist of (1) Annual Reports, (2) Monographs, (3) Professional Papers, (4) Bulletins, (5) Mineral Resources, (6) Water-Supply and Irrigation Papers, (7) Topographic Atlas of the United States—folios and separate sheets thereof, (8) Geologic Atlas of the United States—folios thereof. The classes numbered 2, 7, and 8 are sold at cost of publication; the others are distributed free. A circular giving complete lists may be had on application.

The Professional Papers, Bulletins, and Water-Supply Papers treat of a variety of subjects, and the total number issued is large. They have therefore been classified into the following series: A, Economic geology; B, Descriptive geology; C, Systematic geology and paleontology; D, Petrography and mineralogy; E, Chemistry and physics; F, Geography; G, Miscellaneous; H, Forestry; I, Irrigation; J, Water storage; K, Pumping water; L, Quality of water; M, General hydrographic investigations; N, Water power; O, Underground waters; P, Hydrographic progress reports. This paper is the thirtieth in Series D and the forty-second in Series E, the complete lists of which follow. (PP=Professional Paper; B=Bulletin.)

SERIES D, PETROGRAPHY AND MINERALOGY.

B 1. On hypersthene-andesite and on triclinic pyroxene in augitic rocks, by Whitman Cross, with a geological sketch of Buffalo Peaks, Colorado, by S. F. Emmons. 1883. 42 pp., 2 pls.
B 8. On secondary enlargements of mineral fragments in certain rocks, by R. D. Irving and C. R. Van Hise. 1884. 56 pp., 6 pls. (Out of stock.)
B 12. A crystallographic study of the thinolite of Lake Lahontan, by E. S. Dana. 1884. 34 pp., 3 pls. (Out of stock.)
B 17. On the development of crystallization in the igneous rocks of Washoe, Nevada, with notes on the geology of the district, by Arnold Hague and J. P. Iddings. 1885. 44 pp. (Out of stock.)
B 20. Contributions to the mineralogy of the Rocky Mountains, by Whitman Cross and W. F. Hillebrand. 1885. 114 pp., 1 pl. (Out of stock.)
B 28. The gabbros and associated hornblende rocks occurring in the neighborhood of Baltimore, Maryland, by G. H. Williams. 1886. 78 pp., 4 pls. (Out of stock.)
B 38. Peridotite of Elliott County, Kentucky, by J. S. Diller. 1887. 31 pp., 1 pl. (Out of stock.)
B 59. The gabbros and associated rocks in Delaware, by F. D. Chester. 1890. 45 pp., 1 pl. (Out of stock.)
B 61. Contributions to the mineralogy of the Pacific coast, by W. H. Melville and Waldemar Lindgren. 1890. 40 pp., 3 pls. (Out of stock.)
B 62. The greenstone-schist areas of the Menominee and Marquette regions of Michigan; a contribution to the subject of dynamic metamorphism in eruptive rocks, by G. H. Williams; with introduction by R. D. Irving. 1890. 241 pp., 16 pls. (Out of stock.)
B 66. On a group of volcanic rocks from the Tewan Mountains, New Mexico, and on the occurrence of primary quartz in certain basalts, by J. P. Iddings. 1890. 34 pp.
B 74. The minerals of North Carolina, by F. A. Genth. 1891. 119 pp. (Out of stock.)
B 79. A late volcanic eruption in northern California and its peculiar lava, by J. S. Diller. 1891. 33 pp., 17 pls. (Out of stock.)
B 89. Some lava flows of the western slope of the Sierra Nevada, California, by F. L. Ransome. 1898. 74 pp., 11 pls.
B 107. The trap dikes of the Lake Champlain region, by J. F. Kemp and V. F. Masters. 1893. 62 pp., 4 pls. (Out of stock.)
B 109. The eruptive and sedimentary rocks on Pigeon Point, Minnesota, and their contact phenomena, by W. S. Bayley. 1893. 121 pp., 16 pls.
B 126. A mineralogical lexicon of Franklin, Hampshire, and Hampden counties, Massachusetts, by B. K. Emerson. 1895. 180 pp., 1 pl.
B 136. Volcanic rocks of South Mountain, Pennsylvania, by Florence Bascom. 1896. 124 pp., 28 pls.
B 150. The educational series of rock specimens collected and distributed by the United States Geological Survey, by J. S. Diller. 1898. 400 pp., 47 pls.
B 157. The gneisses, gabbro-schists, and associated rocks of southwestern Minnesota, by C. W. Hall. 1899. 160 pp., 27 pls.
PP 3. Geology and petrography of Crater Lake National Park, by J. S. Diller and H. B. Patton. 1902. 167 pp., 19 pls.
B 209. The geology of Ascutney Mountain, Vermont, by R. A. Daly. 1903. 122 pp., 7 pls.
PP 14. Chemical analyses of igneous rocks published from 1884 to 1900, with a critical discussion of the character and use of analyses, by H. S. Washington. 1903. 495 pp.
PP 18. Chemical composition of igneous rocks expressed by means of diagrams, with reference to rock classification on a quantitative chemico-mineralogical basis, by J. P. Iddings. 1903. 98 pp., 8 pls.
B 220. Mineral analyses from the laboratories of the United States Geological Survey, 1880 to 1903, tabulated by F. W. Clarke, chief chemist. 1903. 119 pp.
B 228. Analyses of rocks from the laboratory of the United States Geological Survey, 1880 to 1903, tabulated by F. W. Clarke, chief chemist. 1904. 375 pp.
PP 28. The superior analyses of igneous rocks from Roth's tabellen, 1869 to 1884, arranged according to the quantitative system of classification, by H. S. Washington. 1904. 68 pp.
B 235. A geological reconnaissance across the Cascade Range near the forty-ninth parallel, by G. O. Smith and F. C. Calkins. 1904. 103 pp., 4 pls.
B 237. Igneous rocks of the Highwood Mountains, Montana, by L. V. Pirsson. 1904. 208 pp., 7 pls.
B 239. Rock cleavage, by C. K. Leith. 1904. 216 pp., 27 pls.

SERIES E, CHEMISTRY AND PHYSICS.

B 9. Report of work done in the Washington laboratory during the fiscal year 1883-84, by F. W. Clarke and T. M. Chatard. 1884. 40 pp. (Out of stock.)
B 14. Electrical and magnetic properties of the iron carburets, by Carl Barus and Vincent Strouhal. 1885. 238 pp. (Out of stock.)
B 27. Report of work done in the Division of Chemistry and Physics, mainly during the year 1884-85, 1886. 80 pp.
B 32. Lists and analyses of the mineral springs of the United States (a preliminary study), by Albert C. Peale. 1886. 235 pp. (Out of stock.)
B 35. Physical properties of the iron carburets, by Carl Barus and Vincent Strouhal. 1886. 62 pp.
B 36. Subsidence of fine solid particles in liquids, by Carl Barus. 1886. 58 pp. (Out of stock.)
B 42. Report of work done in the Division of Chemistry and Physics, mainly during the fiscal year 1885-86, by F. W. Clarke. 1887. 152 pp., 1 pl. (Out of stock.)
B 47. Analyses of waters of the Yellowstone National Park, with an account of the methods of analyses employed, by Frank Austin Gooch and James Edward Whitfield. 1888. 84 pp. (Out of stock.)
B 52. Subaerial decay of rocks and origin of the red color of certain formations, by Israel Cook Russell. 1889. 65 pp., 5 pls. (Out of stock.)
B 54. On the thermoelectric measurement of high temperatures, by Carl Barus. 1889. 313 pp., 11 pls. (Out of stock.)
B 55. Report of work done in the Division of Chemistry and Physics, mainly during the fiscal year 1886-87, by F. W. Clarke. 1889. 96 pp. (Out of stock.)
B 60. Report of work done in the Division of Chemistry and Physics, mainly during the fiscal year 1887-88. 1890. 174 pp. (Out of stock.)
B 64. Report of work done in the Division of Chemistry and Physics, mainly during the fiscal year 1888-89, by F. W. Clarke. 1890. 60 pp.
B 68. Earthquakes in California in 1889, by James Edward Keeler. 1890. 25 pp.
B 73. The viscosity of solids, by Carl Barus. 1891. xii, 139 pp., 6 pls.
B 78. Report of work done in the Division of Chemistry and Physics, mainly during the fiscal year 1889-90, by F. W. Clarke. 1891. 131 pp. (Out of stock.)
B 90. Report of work done in the Division of Chemistry and Physics, mainly during the fiscal year 1890-91, by F. W. Clarke. 1892. 77 pp.
B 92. The compressibility of liquids, by Carl Barus. 1892. 96 pp., 29 pls.
B 94. The mechanism of solid viscosity, by Carl Barus. 1892. 138 pp.
B 95. Earthquakes in California in 1890 and 1891, by Edward Singleton Holden. 1892. 31 pp.
B 96. The volume thermodynamics of liquids, by Carl Barus. 1892. 100 pp.
B 103. High temperature work in igneous fusion and ebullition, chiefly in relation to pressure, by Carl Barus. 1893. 57 pp., 9 pls.
B 112. Earthquakes in California in 1892, by Charles D. Perrine. 1893. 57 pp.
B 113. Report of work done in the Division of Chemistry and Physics during the fiscal years 1891-92 and 1892-93, by F. W. Clarke. 1893. 115 pp.
B 114. Earthquakes in California in 1893, by Charles D. Perrine. 1894. 23 pp.
B 125. The constitution of the silicates, by F. W. Clarke. 1895. 100 pp. (Out of stock.)
B 129. Earthquakes in California in 1894, by Charles D. Perrine. 1895. 25 pp.
B 147. Earthquakes in California in 1895, by Charles D. Perrine. 1896. 23 pp.
B 148. Analyses of rocks, with a chapter on analytical methods, laboratory of the United States Geological Survey, 1880 to 1896, by F. W. Clarke and W. F. Hillebrand. 1897. 306 pp. (Out of stock.)
B 155. Earthquakes in California in 1896 and 1897, by Charles D. Perrine. 1898. 47 pp.
B 161. Earthquakes in California in 1898, by Charles D. Perrine. 1899. 31 pp., 1 pl.
B 167. Contributions to chemistry and mineralogy from the laboratory of the United States Geological Survey; Frank W. Clarke, Chief Chemist. 1900. 166 pp.
B 168. Analyses of rocks, laboratory of the United States Geological Survey, 1880 to 1899, tabulated by F. W. Clarke. 1900. 308 pp. (Out of stock.)
B 176. Some principles and methods of rock analysis, by W. F. Hillebrand. 1900. 114 pp.
B 186. On pyrite and marcasite, by H. N. Stokes. 1900. 50 pp.
B 207. The action of ammonium chloride upon silicates, by F. W. Clarke and George Steiger. 1902. 57 pp. (Out of stock.)
PP 14. Chemical analyses of igneus rocks published from 1884 to 1900, with a critical discussion of the character and use of analyses, by H. S. Washington. 1903. 495 pp.
PP 18. Chemical composition of igneus rocks expressed by means of diagrams, with reference to rock classification on a quantitative chemico-mineralogical basis, by J. P. Iddings. 1903. 98 pp., 8 pls.
B 220. Mineral analyses from the laboratories of the United States Geological Survey, 1880 to 1903, tabulated by F. W. Clarke, chief chemist. 1903. 119 pp.
B 228. Analyses of rocks from the laboratory of the United States Geological Survey, 1880 to 1903, tabulated by F. W. Clarke, chief chemist. 1904. 375 pp.
PP 28. The superior analyses of igneous rocks from Roth's Tabellen, 1869 to 1884, arranged according to the quantitative system of classification, by H. S. Washington. 1904. 68 pp.
B 239. Rock cleavage; by C. K. Leith. 1904. 216 pp., 27 pls.

Correspondence should be addressed to—

The Director,

United States Geological Survey,

Washington, D. C.

January, 1905.

[Mount each slip upon a separate card, placing the subject at the top of the second slip. The name of the series should not be repeated on the series card, but the additional numbers should be added, as received, to the first entry.]

Author.

Leith, Charles Kenneth.

. . . Rock cleavage, by Charles Kenneth Leith. Washington, Gov't print. off., 1904 [1905]

216, iii p. illus., 27 pl., diagrs. $23\frac{1}{2}^{cm}$. (U. S. Geological survey. Bulletin no. 239.)

Subject series: D, Petrography and mineralogy, 30; E, Chemistry and physics, 42.

"Literature on secondary rock cleavage": p. 13–14.

1. Rocks—Cleavage.

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Leith, Charles Kenneth.

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no. 239. Leith, C. K. Rock cleavage. 1904.

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U. S. Geological survey.

58th Congress, 2d Session. | HOUSE OF REPRESENTATIVES. | Document No. 774.

Bulletin No. 240 | Series G, Miscellaneous, 28

DEPARTMENT OF THE INTERIOR

UNITED STATES GEOLOGICAL SURVEY

CHARLES D. WALCOTT, Director

BIBLIOGRAPHY AND INDEX

OF

NORTH AMERICAN GEOLOGY, PALEONTOLOGY, PETROLOGY, AND MINERALOGY

FOR

THE YEAR 1903

BY

FRED BOUGHTON WEEKS

WASHINGTON
GOVERNMENT PRINTING OFFICE
1904

CONTENTS.

LETTER OF TRANSMITTAL.

Department of the Interior,
United States Geological Survey,
Washington, D. C., June 7, 1904.

Sir: I have the honor to transmit herewith the manuscript of a bibliography and index of North American geology, paleontology, petrology, and mineralogy for the year 1903, and to request that it be published as a bulletin of the Survey.

Very respectfully,

F. B. Weeks,
Librarian.

Hon. Charles D. Walcott,
Director United States Geological Survey.

BIBLIOGRAPHY AND INDEX OF NORTH AMERICAN GEOLOGY, PALEONTOLOGY, PETROLOGY, AND MINERALOGY FOR THE YEAR 1903.

By Fred Boughton Weeks.

INTRODUCTION.

The arrangement of the material of the Bibliography and Index for 1903 is similar to that adopted for the preceding annual bibliographies, Bulletins Nos. 130, 135, 146, 149, 156, 162, 172 (combined in Bulletins 188 and 189), 203, and 221.

Bibliography.—The bibliography consists of full titles of separate papers, arranged alphabetically by authors' names, an abbreviated reference to the publication in which the paper is printed, and a brief description of the contents, each paper being numbered for index reference.

Index.—The subject headings, their subdivisions and arrangement, are shown in the classified key to the index, which immediately precedes the index. Reference is made in each entry by author's name and number of article in the bibliography.

The series of annual bibliographies has been prepared solely from publications received by the library of the United States Geological Survey. On January 1, 1903, the writer was placed in charge of the library of this organization, and an effort has since been made to procure the publications which were not noticed in the bibliographies of previous years, it being known that there were a considerable number of omissions of geological papers. Many of these are noted in this bulletin.

Mr. John M. Nickles has again assisted in the compilation of this work, and credit is due him for its careful preparation and completeness.

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Annals and Magazine of Natural History, 7th ser., vols. 11 and 12, 1903. London, England.

Appalachia, vol. 10, no. 2, 1903. Boston, Mass.

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Boston Society of Natural History: Proceedings, vol. 31, nos. 1–6, 1903. Boston, Mass.

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2 **Adams** (Frank D.). Memoir of George M. Dawson.
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3 —— The Monteregian Hills—a Canadian petrographical province.
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Describes occurrence, stratigraphy, and lithologic characters of the Red Beds of Texas, Oklahoma, Indian Territory, and Kansas, and discusses their relationships.

7 —— Zinc and lead deposits of northern Arkansas.
U. S. Geol. Surv., Bull. no. 213, pp. 187–196, 1903.
Gives a brief account of the position, history of development and geologic structure of the field, and describes the occurrence, character, and source of the ores.

8 —— Zinc and lead deposits of northern Arkansas.
Am. Inst. Mg. Engrs., Trans. (Albany meeting, February, 1903). 12 pp.
Describes the geologic position, occurrence, and character of the zinc and lead ore deposits, and discusses their classification and origin.

9 **Adams** (George I.). Origin of bedded breccias in northern Arkansas.
Abstract: Science, new ser., vol. 17, pp. 792–793, 1903.

10 —— **Girty** (George H.), and **White** (David). Stratigraphy and paleontology of the Upper Carboniferous rocks of the Kansas section.
U. S. Geol. Surv., Bull. no. 211, 123 pp., 4 pls., 10 figs., 1903.
Comprises a review of previous work upon the stratigraphy, and a description in detail of the geologic formations, including definition and synonymy, character and extent, and faunal lists of the Upper Carboniferous strata of Kansas and northern Indian Territory, by George I. Adams; a discussion and tabulation of the invertebrate fossils, by George H. Girty, and an annotated list of the fossil plants recorded from the Upper Carboniferous and Permian formations of Kansas, by David White.

11 **Adams** (Thomas K.). Lower productive Coal Measures of the bituminous regions of Pennsylvania; the importance of a knowledge of their characteristic features.
Mines & Minerals, vol. 23, pp. 348–352, 3 figs., 1903.
Describes the geology of the Coal Measures of the bituminous coal regions of Pennsylvania.

12 **Aiken** (P. B.). The mines of Santa Eulalia, Mexico.
Mg. & Sci. Press, vol. 87, p. 402, 1 fig., 1903.
Describes briefly the general geology and the occurrence of the silver-lead ores.

13 **Alden** (William C.). The stone industry in the vicinity of Chicago, Ill.
U. S. Geol. Surv., Bull. no. 213, pp. 357–360, 1903.
Describes the occurrence and utilization of limestone, sand, and gravel in the vicinity of Chicago, Ill.

14 —— **Fuller** (Myron L.) and. Elkland–Tioga folio, Pennsylvania.
See Fuller (M. L.) and Alden (W. C.), 424.

15 —— **Fuller** (Myron L.) and. Gaines folio, Pennsylvania–New York.
See Fuller (M. L.) and Alden (W. C.), 423.

16 **Aldrich** (Truman H.). New species of Tertiary fossils from Alabama, Mississippi, and Florida.
Nautilus, vol. 16, pp. 97–101, pls. 3–4, 1903.

17 —— A new Conus from the Tertiary of Florida.
Nautilus, vol. 16, pp. 131–132, 2 figs., 1903.

18 —— Two new species of Eocene fossils from the Lignitic of Alabama.
Nautilus, vol. 17, pp. 19–20, figs. 1–2, 1903.

19 —— **Smith** (Eugene A.) and. The Grand Gulf formation.
See Smith (E. A.) and Aldrich (T. H.), 1127.

20 **Ami** (Henry M.). Bibliography of Canadian geology and paleontology for the year 1901.

Can. Roy. Soc., Proc. & Trans., 2d ser., vol. 8, sec. 4, pp. 169–182, 1902.

21 —— Bibliography of Dr. George M. Dawson.

Can. Roy. Soc. Proc. & Trans., 2d ser., vol. 8, sec. 4, pp. 192–201, 1902.

22 —— Paleontology and chronological geology.

Can. Geol. Surv., Summ. Rept. for 1902, pp. 317–335, 1903.

Gives a statement of the paleontological work of the year, discusses records of borings, and gives notes upon the geology of Victoria Cove, Quebec.

23 —— On the Upper Cambrian age of the Dictyonema slates of Angus Brook, New Canaan and Kentville, N. S. [Canada].

Nova Scotian Inst. Sci., Proc. & Trans., vol. 10, pp. 447–450, 1903.

24 —— Sketch of the life and work of the late Dr. A. R. C. Selwyn, C. M. G., LL. D., F. R. S., F. G. S., etc., Director of the Geological Survey of Canada from 1869 to 1894.

Am. Geol., vol. 31, pp. 1–21, 1 pl. (por.), 1903.

25 —— Ordovician succession in eastern Ontario.

Abstract: Geol. Soc. Am., Bull., vol. 13, pp. 517–518, 1903.

Presents a list of the formations and gives their lithologic characters.

26 —— Meso-Carboniferous age of the Union and Riversdale formations, Nova Scotia.

Abstract: Geol. Soc. Am., Bull., vol. 13, pp. 533–535, 1903.

Contains additional data on the age and relations of these formations.

27 —— The first Eparchæan formation.

Abstract: Science, new ser., vol. 17, p. 290, 1903.

28 —— See Adams (F. D.), 2.

29 **Anderson** (Frank M.). Physiography and geology of the Siskiyou Range.

Abstract: Eng. & Mg. Jour., vol. 75, p. 154, 1903; Jour. Geol., vol. 11, p. 100, 1903.

30 **Anderson** (Tempest). Characteristics of recent volcanic eruptions.

Nature, vol. 67, p. 308, 1903.

Describes phenomena exhibited in the eruptions of Soufrière and Mont Pelée.

31 —— Recent volcanic eruptions in the West Indies.

Geog. Jour., vol. 31, pp. 265–279, 13 pls., 1903; Yorkshire Phil. Soc., Ann. Rept. for 1903.

Describes volcanic phenomena and physiographic changes produced by the eruptions of 1902 in St. Vincent and Martinique.

32 **Anderson** (Tempest) and **Flett** (John S.). Preliminary report on the recent eruption of the Soufrière in St. Vincent, and of a visit to Mont Pelée, in Martinique.

Smith. Inst., Ann. Rept. for 1902, pp. 309–330, pls. 1–3, 1903.

See no. 35 of U. S. Geol. Surv., Bull. no. 221, 1903.

33 —— and **Flett** (John S.). Report on the eruptions of the Soufrière, in St. Vincent, in 1902, and on a visit to Montagne Pelée, in Martinique. Part I.

London Roy. Soc., Phil. Trans., ser. A, vol. 200, pp. 353–553, pls. 21–39, 1903.

Describes physiographic features and general geology of St. Vincent, the phenomena of the eruptions of the Soufrière of May, 1902, and geologic and physiographic changes resulting, and discusses and compares the eruption phenomena of the Soufrière and Montagne Pelée.

34 **Andrews** (C. L.). Muir glacier [Alaska].

Nat. Geog. Mag., vol. 14, pp. 441–445, ill., 1903.

Describes the appearance of the glacier in 1903. An appended note by G. K. Gilbert gives data in regard to the glacier.

35 **Argall** (P. H.). Pelée's obelisk.

Eng. & Mg. Jour., vol. 76, p. 420, 1903.

Discusses the formation of the obelisk in the crater of Mt. Pelé.

36 **Argall** (Philip). Notes on the Santa Eulalia mining district, Chihuahua, Mexico.

Colo. Sci. Soc., Proc., vol. 7, pp. 117–126, figs. 1–4, 1903.

Gives observations on the geology and the occurrence and character of the ore deposits.

37 —— The Santa Eulalia [Mexico] ore deposits.

Eng. & Mg. Jour., vol. 76, pp. 350–351, ill., 1903.

Describes the general geology, the igneous intrusions, the occurrence and character of the silver-lead ores, and discusses their origin.

38 **Arnold** (Ralph). The paleontology and stratigraphy of the marine Pliocene and Pleistocene of San Pedro, California.

Cal. Acad. Sci., Mem., vol. 3, pp. 1–420, pls. 1–37, 1903; Leland Stanford jr. Univ., Cont. to Biol. from the Hopkins Seaside Laboratory, 31, pp. 1–420, pls. 1–37, 1903.

Describes the topography and the character and occurrence of Tertiary and Quaternary formations of California bordering the Pacific, and gives lists of fossils by formations showing geographical distribution and relations to existing faunas, and systematic descriptions of the genera and species. Includes descriptions of several new species of corals by T. Wayland Vaughan and of mollusca by W. H. Dall.

39 **Arreola** (José Maria). The recent eruptions of Colima [Mexico].

Jour. Geol., vol. 11, pp. 749–761, figs. 1–8, 1903.

Gives a chronologic record of the activity of the volcano Colima and discusses volcanic phenomena.

40 **Ashley** (George Hall). The geology of the Lower Carboniferous area of southern Indiana.

Ind., Dept. Geol. & Nat. Res., 27th Ann. Rept., pp. 49–122, pls. 1–13, figs. 1–3, 1903.

Describes physiographic and drainage features, the stratigraphy, character, occurrence and geologic relations of Lower Carboniferous formations and economic resources of this area.

41 —— **Fuller** (Myron L.) and. Recent work in the coal field of Indiana and Illinois.

See Fuller (M. L.) and Ashley (G. H.), 425.

42 **Austin** (W. L.). Some tellurium veins in La Plata Mountains [Colorado].

Colo. Sci. Soc., Proc., vol. 6, pp. 87–90 [1902].

Describes the occurrence and character of the veins, and the character of the country rock.

43 —— Some New Mexico copper deposits.

Colo. Sci. Soc., Proc., vol. 6, pp. 91–95 [1902].

Describes the occurrence and discusses the origin of the ore deposits.

44 —— The ore deposits of Cananea [Mexico].

Eng. & Mg. Jour., vol. 76, pp. 310–311, figs. 1–2, 1903.

Describes the character and occurrence of the copper ore deposits.

45 —— [In discussion of paper by Walter Harvey Weed, "Ore-deposits near igneous contacts."]

Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 1070–1077, 1903.

Describes occurrences of some ore deposits and their bearing upon the paper discussed.

46 —— [In discussion of paper by Waldemar Lindgren, "The geological features of the gold production of North America."]

Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 1079–1081, 1903.

Calls attention to the occurrence of a gold deposit of supposed Cambrian age in Colorado.

B.

47 **Bache** (Franklin). The Arkansas-Indian Territory coal-field.

Eng. & Mg. Jour., vol. 76, pp. 390–392, ill., 1903.

Describes the location and extent of the field, the character and occurrence of the coal seams, and the mining developments.

48 **Bagg** (Rufus M., jr.). The genesis of ore deposits in Boulder County, Colorado.

Abstract: Eng. & Mg. Jour., vol. 75, p. 154, 1903; Jour. Geol., vol. 11, p. 100, 1903.

49 —— The veins of Boulder County, Colorado.

Eng. & Mg. Jour., vol. 75, p. 334, 1903.

Discusses the occurrence and the origin of the ore deposits.

50 **Bailey** (Edgar H. S.). Special report on mineral waters [Kansas].
Kans. Univ. Geol. Surv., vol. 7, 343 pp., 38 pls., 1902.

51 **Bailey** (J. Trowbridge). The ore deposits of Contact, Nevada.
Eng. & Mg. Jour., vol. 76, pp. 612–613, ill., 1903.
Describes observations upon the geology of the region and discusses the occurrence and origin of the ore deposits.

52 **Bailey** (L. W.). Geological observations in northern New Brunswick.
Can. Geol. Surv., Summ. Rept. for 1902, pp. 382–388, 1903.
Describes observations upon the geology of the region examined

53 —— Notes on the highlands of northern New Brunswick.
New Brunswick Nat. Hist. Soc., Bull., no. 21 (vol. 5, pt. 1), pp. 93–101, 1903.
Contains observations on the geology of the region.

54 **Baker** (Frank C.). Pleistocene mollusks of White Pond, New Jersey.
Nautilus, vol. 17, pp. 38–39, 1903.
Gives a list of and notes upon the molluscan fauna of this locality.

55 **Bancroft** (Geo. J.). The Yaqui River country of Sonora, Mexico.
Eng. & Mg. Jour., vol. 76, pp. 160–162, ill., 1903.
Contains observations on placer deposits of gold.

56 **Barbour** (Erwin Hinckley). Report of the State geologist.
Nebr. Geol. Surv., vol. 1, 258 pp., 13 pls., 166 figs., 1903.
Describes physiography, hydrography, drainage and water resources, stratigraphy and general geological relations of formations, with lists of fossils contained therein, mineral resources and economic products.

57 —— Present knowledge of the distribution of Daimonelix.
Science, new ser., vol. 18, pp. 504–505, 1903.

58 **Barlow** (Alfred E.). The Sudbury mining district [Ontario].
Can. Geol. Surv., Summ. Rept. for 1902, pp. 252–267, 1903.
Describes petrographic characters of rock types and discusses the occurrence, character, and origin of nickel and copper ore deposits.

59 **Baskerville** (Charles). Kunzite, a new gem.
Science, new ser., vol. 18, pp. 303–304, 1903.
Describes characters of the spodumene obtained from San Diego County, California, and gives to this gem the name of Kunzite.

60 **Bassler** (Ray S.). The structural features of the bryozoan genus Homotrypa, with descriptions of species from the Cincinnatian Group.
U. S. Nat. Mus., Proc., vol. 26, pp. 565–591, pls. 20–25, 1903.

61 **Beasley** (Walter L.). Evolution of the horse.
Sci. Am., vol. 88, pp. 451–452, ill., 1903

62 **Beasley** (Walter L.). A remarkable fossil discovery.
Sci. Am., vol. 89, p. 87, ill., 1903.
Describes the discovery of a large skull of Triceratops, and the probable habits, size, appearance, etc., of the animal.

63 **Beecher** (Charles E.). Observations on the genus Romingeria.
Am. Jour. Sci., 4th ser., vol. 16, pp. 1–11, pls. 1–4, 1903.
Reviews the history of the genus and type species and describes the type and other species.

64 **Beede** (Joshua W.). Carboniferous invertebrates.
Kans. Univ. Geol. Surv., vol. 6, pp. 1–187, pls. 1–22, figs. 1–4, 1900.

65 **Beeler** (Henry C.). A brief review of the South Pass gold district, Fremont County, Wyoming.
12 pp., 1903. [Privately printed?]
Includes a brief account of the geology of the region.

66 **Bell** (Robert). Summary report on the operations of the Geological Survey of Canada for the calendar year 1902.
Can. Geol. Surv., Summ. Rept. for 1902, pp. 1–482, 1903.
Reviews the operations of the year of the Geological Survey of Canada. Includes reports by officials of the survey.

67 **Bell** (Robert N.). Tin ledges in Alaska.
Eng. & Mg. Jour., vol. 76, p. 820, 1903.
Describes the discovery of ledges containing tin ore in the vicinity of Port Clarence, Alaska.

68 —— Tin in Alaska.
Mg. & Sci. Press, vol. 87, p. 351, 1903.
Describes the occurrence of tin-ore deposits.

69 **Bennett** (Frank, jr.) and **Jones** (Grove B.). Soil survey of the Brazoria area, Texas.
U. S. Dept. Agric., Field Oper. Bur. Soils, 1902, 4th Rept., pp. 349–364, pls. 19–20, 1903.
Includes a brief account of the physiography and geology.

70 —— **Smith** (W. G.) and. Soil survey of the Lebanon area, Pennsylvania.
See Smith (W. G.) and Bennett (Frank, jr.), 1142.

71 **Bensley** (B. Arthur). On the identification of Meckelian and mylohyoid grooves in the jaws of Mesozoic and recent mammalia.
Toronto Univ. Studies, Biol. ser., no. 3, 9 pp., 1 pl., 1902.

72 **Bergeat** (Alfred). Die Produkte der letzten Eruption am Vulkan S. Maria in Guatemala (Oktober 1902).
Centralbl. f. Min., pp. 112–117, 1903.
Describes character and composition of material ejected by the volcano S. Maria.

73 **Bergeat** (Alfred). Einige weitere Bemerkungen über die Produkte des Ausbruchs am Sta. Maria, Guatemala.

Centralbl. f. Min., pp. 290–291, 1903.

Gives results of investigations upon the composition of ashes ejected by S. Maria, Guatemala.

74 **Berkey** (Charles Peter). A guide to the Dalles of the St. Croix for excursionists and students.

Minneapolis, 40 pp., ill., 1898. (Private publication.)

Describes the geologic history and structure of the region, physiographic and erosion features, and the character and occurrence of Cambrian strata and igneous rocks.

75 **Berry** (Edward W.). New species of plants from the Matawan formation.

Am. Nat., vol. 37, pp. 677–684, figs. 1–9, 1903.

76 —— The flora of the Matawan formation (Crosswicks clays).

N. Y. Bot. Garden, Bull., vol. 3, no. 9, pp. 45–103, pls. 43–57, 1903.

Discusses occurrence and lithologic characters of the Matawan formation and its subdivisions in New Jersey, the character and relationships of the flora collected near Cliffwood, New Jersey, and gives detailed descriptions of the plants.

77 —— Aralia in American paleobotany.

Bot. Gaz., vol. 36, pp. 421–428, 1903.

Discusses leaf characters in fossil species of Aralia.

78 **Beyer** (S. W.) and **Young** (L. E.). Geology of Monroe County [Iowa].

Iowa Geol. Surv., vol. 13, pp. 355–422, pls. 9–10, figs. 54–73, 1903.

Describes topography and drainage, the character, occurrence, and geologic relations of Carboniferous strata and glacial deposits, the character and occurrence of coal seams and coal mining operations in the county, and other economic resources.

79 **Billups** (A. C.). Fossil land shells of the old forest bed of the Ohio River.

Nautilus, vol. 16, pp. 50–52, 1902.

Describes the occurrence and gives a list of and notes upon the species identified.

80 **Blackwelder** (Eliot), **Salisbury** (Rollin D.) and. Glaciation in the Bighorn Mountains.

See Salisbury (R. D.) and Blackwelder (Eliot), 1054.

81 **Blake** (John Charles). A mica-andesite of west Sugarloaf Mountain, Boulder County, Colorado.

Colo. Sci. Soc., Proc., vol. 7, pp. 1–17, 1901.

Describes occurrence, megascopic and microscopic characters, and composition.

82 —— Some relations of tetrahedral combinations to crystalline form.

Colo. Sci. Soc., Proc., vol. 7, pp. 19–21, figs. 1–4, 1901

83 **Blake** (William P.). Arizona diatomite.

Wis. Acad. Sci., Trans., vol 14, pt. 1, pp. 107–111, pls. 3–8, 1903.

Gives notes upon and lists of species of diatoms obtained from deposits of diatomaceous earth in the valley of the San Pedro, Arizona.

84 —— Diatom-earth in Arizona.

Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 38–45, 1903.

Describes occurrence and character of diatomaceous deposits, and discusses their origin and economic value.

85 —— Origin of pebble-covered plains in desert regions.

Eng. & Mg. Jour., vol. 75, p. 632, 1903; Am. Inst. Mg. Engrs., Trans. (Albany meeting, February, 1903).

86 —— Tombstone and its mines, a report upon the past and present condition of the mines of Tombstone, Cochise County, Arizona, to the Development Company of America.

New York. 83 pp., ill., 1902.

Describes the general geology of the region, the character and occurrence of the stratified rocks and geologic structure, and the occurrence of the ore deposits of precious metals, and discusses their origin.

87 —— Tombstone and its mines.

Am. Inst. Mg. Engrs., Trans. (New York meeting, October, 1903). 3 pp.

Gives observations on the occurrence of ore deposits and discusses the origin of certain manganiferous ores.

88 —— Geology of Arizona.

Rept. of the governor of Ariz. to the Secretary of the Interior for the year ended June 30, 1903, pp. 126–135, 1903.

Gives a general outline of the geology of Arizona.

89 **Blatchford** (John). The Postdam formation of Bald Mountain district [South Dakota.]

Mg. & Sci. Press, vol. 87, p. 167, 1903.

Describes the occurrence of the ore deposits.

90 **Blatchley** (W. S.). The mineral waters of Indiana: their location, origin, and character.

Ind. Dept. Geol. & Nat. Res., 26th Ann. Rept., pp. 11–158, pls. 1–19, 1903.

91 —— On the petroleum industry in Indiana in 1901.

Ind. Dept. Geol. & Nat. Res., 26th Ann. Rept., pp. 303–331, 1903.

92 —— Gold and diamonds in Indiana.

Ind. Dept. Geol. & Nat. Res., 27th Ann. Rept., pp. 11–47, pls. 1–4, figs. 1–3, 1903.

Describes glacial history in Indiana and discusses the occurrence of gold and diamonds in glacial drift deposits.

93 —— and **Sheak** (W. H.). Trenton rock petroleum.

Sci. Am. Suppl., vol. 55, p. 22775, 1903.

Discusses occurrence and origin of petroleum in Trenton rock.

94 **Boehmer** (Max). Some practical suggestions concerning the genesis of ore-deposits.

Am. Inst. Mg. Engrs., Trans. (British Columbia meeting, July, 1903). 6 pp.

95 [**Bogdanovitch**, K. 1.]. [Sketch of Nome [Alaska]].

St. Petersburg, 116 pp., ill., 1901. [Russian]

96 **Böggild** (O. B.). On some minerals from the nephelite-syenite at Julianehaab, Greenland (erikite and schizolite).

Meddelelser om Grönland, vol. 26, pp. 93–139, figs, 1–19, 1903; Copenhagen Univ., Min. and Geol. Mus., Contr. to Min., no. 2, 1903.

Describes occurrence, constitution, crystallography, and properties of erikite, a new mineral, and schizolite from Greenland.

97 —— Samples of the sea-floor along the coast of east Greenland 74½–70 N. L.

Meddelelser om Grönland, vol. 28, pp. 19–95, pls. 1–9, 1903; Copenhagen Univ., Min. & Geol. Mus., Contr. to Min., no. 3, 1903.

98 **Bolton** (L. L.). Round Lake to Abitibi River [Ontario].

Ontario Bur. Mines [12th] Rept. pp. 173–190, 1903.

Contains observations on the geography, geology, petrology, and resources of the region traversed.

99 **Bonney** (T. G.). Notes on specimens collected by Professor Collie, F. R. S., in the Canadian Rocky Mountains.

Geol. Mag., new ser., dec. 4, vol. 10, pp. 289–297, pl. 17, fig. 1, 1903.

Discusses occurrence and character of rock specimens from Canadian localities.

100 —— Note on rock specimens from the Canadian Rocky Mountains.

Geog. Jour., vol. 31, pp. 498–499, 1903.

101 —— March dust from the Soufrière.

Nature, vol. 67, p. 584, 1903.

Describes character of volcanic dust from an eruption of the Soufrière of St. Vincent.

102 **Bonsteel** (Jay A.). Soil survey of St. Mary County, Md.

U. S. Dept. Agric., Field Oper. Div. Soils, 1900, 2d Rept. pp. 125–145, 901.

Includes a brief account of the physiography and geology.

103 —— and **Burke** (R. T. Avon). Soil survey of Calvert County, Md.

U. S. Dept. Agric., Field Oper. Div. Soils, 1900, 2d Rept., pp. 147–171, 1901.

Includes an account of the physiography and geology.

104 —— Soil survey of Kent County, Md.

U. S. Dept. Agric., Field Oper. Div. Soils, 1900, 2d Rept., pp. 173–186, 1901.

Includes a brief account of the geology and physiography.

105 **Bonsteel** (Jay A.) and **Taylor** (F. W.). Soil survey of the Salem area, New Jersey.

U. S. Dept. Agric., Field Oper. Bur. Soils, 1901, 3d Rept., pp. 125–148, 1902.

Includes a brief account of the physiography and geology.

106 —— and party. Soil survey of Prince George County, Maryland.

U. S. Dept. Agric., Field Oper. Bur. Soils, 1901, 3d Rept., pp. 173–210, pls. 21–25, 1902.

Includes an account of the physiography and geology.

107 —— and party. Soil survey of the Yazoo area, Mississippi.

U. S. Dept. Agric., Field Oper. Bur. Soils, 1901, 3d Rept., pp. 359–388, pls. 44–52, 1902.

Includes an account of the physiography and geology.

108 —— and party. Soil survey of Tazewell County, Illinois.

U. S. Dept. Agric., Field Oper. Bur. Soils, 1902, 4th Rept., pp. 465–489, 1903.

Includes a short account of the physiography and geology.

109 —— and party. Soil survey of Clinton County, Illinois.

U. S. Dept. Agric., Field Oper. Bur. Soils, 1902, 4th Rept., pp. 491–505, 1903.

Includes a short account of the physiography and geology.

110 —— Soil survey of the Janesville area, Wisconsin.

U. S. Dept. Agric., Field Oper. Bur. Soils, 1902, 4th Rept., pp. 549–570, pls. 30–32, 1903.

Includes a short account of the physiography and geology.

111 —— **Dorsey** (Clarence W.) and. Soil survey of Cecil County, Md.

See Dorsey (C. W.) and Bonsteel (J. A.), 313.

112 —— **Dorsey** (Clarence W.) and. Soil survey in the Connecticut Valley.

See Dorsey (C. W.) and Bonsteel (J. A.), 310.

113 —— **Mooney** (Charles N.) and. Soil survey of the Albemarle area, Virginia.

See Mooney (C. N.) and Bonsteel (F. E.), 917.

114 **Böse** (Emilio). Breve noticia sobre el estado actual de volcan de Tacana (Chiapas) [Mexico].

Soc. Cient. Ant. Alz., Mem. y Rev., vol. 18, pp. 267–270, pl. 15, 1902.

Describes the present condition of this volcano.

115 **Boutwell** (J. M.). Progress report on the Park City mining district, Utah.

U. S. Geol. Surv., Bull. no. 213, pp. 31–40, 1903.

Contains a general account of the geology and ore deposits of the region.

116 **Boutwell** (J. M.). Ore deposits of Bingham, Utah.

U. S. Geol. Surv., Bull. no. 213, pp. 105–122, 1903.

Describes the history of mining developments at this locality, the character and occurrence of sedimentary and igneous rocks, the geologic structure, and the occurrence and character of the ore deposits.

117 **Bownocker** (John Adams). The central Ohio natural gas fields.

Am. Geol., vol. 31, pp. 218–231, pl. 14, 1903; Ohio St. Univ. Bull., ser. 7, no. 13 (Geol. Ser. no. 5), 1903.

Describes location and area, history and development, geological structure of the natural gas fields and sections of the wells bored, and the production and composition of the gas.

117 a —— The occurrence and exploitation of petroleum and natural gas in Ohio.

Ohio Geol. Surv., 4th ser., Bull. no. 1, pp. 9–320, pls. 1–6, and 9 maps., 1903.

Gives a detailed account of the oil and gas producing horizons of Ohio rocks, records of borings, history, development, and production of the various fields, including the stratigraphy and geologic structure.

118 **Branner** (John C.). A topographic feature of the hanging valleys of the Yosemite [California].

Jour. Geol., vol. 11, pp. 547–553, figs. 1–5, 1903.

Gives an explanation for the position of the falls.

119 —— Notes on the geology of the Hawaiian Islands.

Am. Jour. Sci., 4th ser., vol. 16, pp. 301–316, pl. 15, figs. 1–13, 1903.

Describes topographic features and discusses their origin.

120 **Brauns** (R.). Asche des Vulkans Sta. Maria in Guatemala.

Centralblatt für Min., pp. 132–134, 1903.

Describes the composition of ashes ejected by St. Maria in Guatemala.

121 —— Ueber die Asche des Vulkans Sta. Maria in Guatemala.

Centralbl. f. Min., p. 290, 1903.

Discusses differences and their explanation, in composition of volcanic ashes from St. Maria in Guatemala found by several investigators.

122 **Breed** (Robert S.). "The Sunset trachyte," from near Sunset, Boulder County, Colorado.

Colo. Sci. Soc., Proc., vol. 7, pp. 216–230 [1902].

Describes the occurrence, the megascopic and microsopic characters, and the composition.

123 **Breeze** (Fred J.). Some topographic features in the lower Tippecanoe Valley [Indiana].

Ind. Acad. Sci., Proc., 1902, pp. 198–200, 1 fig., 1903.

Describes some physiographic features of the region.

124 **Brent** (Charles). Notes on the gold ores of western Ontario.

Can. Mg. Rev., vol. 22, pp. 33–35, 1903.

Gives notes on the geology of the region and the occurrence of gold ores.

125 **Brewer** (William M.). The rock-slide at Frank, Alberta Territory, Canada.

Inst. Mg. Engrs., Trans., vol. 26, pp. 34–39, figs. 1–2, 1903.

Describes the landslide which occurred at Frank, in Alberta Territory, on April 29, 1903.

126 —— White Horse district, in Yukon Territory—history, geology, present conditions and future prospects of the mining district.

Mines & Minerals, vol. 24, pp. 28–31, 1903.

Describes the general geology of the region and the occurrence of copper ore and coal deposits.

127 —— Mineral resources of southeastern Alaska.

Mg. & Sci. Press, vol. 86, p. 315, 1903.

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128 —— Mount Sicker mining district, British Columbia.

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129 **Bridgford** (John). Analysis of volcanic dust from La Soufrière.

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130 **Broadhead** (G. C.). Bituminous and asphalt rocks of the United States.

Am. Geol., vol. 32, pp. 59–60, 1903.

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131 **Brock** (R. W.). Preliminary report on the Boundary Creek district, British Columbia.

Can. Geol. Surv., Summ. Rept. for 1902, pp. 90–136, 1903.

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132 **Brooks** (Alfred Hulse). Placer gold mining in Alaska in 1902.

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133 —— Stream tin in Alaska.

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134 **Brown** (Barnum). A new genus of ground sloth from the Pleistocene of Nebraska.

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136 **Buckley** (Ernest Robertson). Highway construction in Wisconsin.

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137 **Buffet** (Edward P.). Some glacial conditions and recent changes on Long Island [New York].

Jour. Geog., vol. 2, pp. 95–101, figs. 1–6, 1903.

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138 **Burgess** (James L.) **Fippin** (Elmer O.) and. Soil survey of Howell County, Missouri.

See Fippin (Elmer O.) and Burgess (J. L.), 401.

139 **Burgess** (John D.). Secondary enrichment.

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140 —— Recent discoveries in Arizona.

Eng. & Mg. Jour., vol. 76, p. 936, 1903.

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141 **Burk** (William E.). Asphalt rock in Kentucky.

Eng. & Mg. Jour., vol. 75, pp. 969–970, 1 fig., 1903.

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142 **Burke** (R. T. Avon) and **Marean** (Herbert W.). Soil survey of the Westfield area, New York.

U. S. Dept. Agric., Field Oper. Bur. Soils, 1901, 3d Rept., pp. 75–92 pls. 2–6, 1902.

Includes a brief account of the topography and geology.

143 —— and **Marean** (Herbert W.). Soil survey of Cobb County, Georgia.

U. S. Dept. Agric., Field Oper. Bur. Soils, 1901, 3d Rept., pp. 317–327, 1902.

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144 —— and **Wilder** (Henry J.). Soil survey of the Trenton area, New Jersey.

U. S. Dept. Agric., Field Oper. Bur. Soils, 1902, 4th Rept., pp. 163–186, 1903.

Includes a brief account of the physiography and geology.

145 —— and party. Soil survey of Perry County, Alabama.

U. S. Dept. Agric., Field Oper. Bur. Soils, 1902, 4th Rept., pp. 309–323, 1903.

Includes a brief account of the physiography and geology.

146 —— **Bonsteel** (Jay A.) and. Soil survey of Calvert County, Md.

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147 **Bush** (Lucy P.). Note on the dates of publication of certain genera of fossil vertebrates.

Am. Jour. Sci., 4th ser., vol. 16, pp. 96–98, 1903.

148 **Butts** (Charles). Fossil faunas of the Olean quadrangle.

N. Y. State Mus., Bull. 69, pp. 990–995, 1903.

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149 **Byrne** (P.). Marble formations of the Cahaba River, in Alabama.

Eng. Assoc. South, Trans., 1901, vol. 12, pp. 48–59, figs. 1–3 [1902].

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Soc. Cient. Ant. Alz., Mem. y Rev., vol. 18, pp. 197–201, 1902.

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151 **Caine** (Thomas A.). Soil survey of the Hickory area, North Carolina.

U. S. Dept. Agric., Field Oper. Bur. Soils, 1902, 4th Rept., pp. 239–258, pl. 8, 1903.

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152 —— and **Mangum** (A. W.). Soil survey of the Mount Mitchell area, North Carolina.

U. S. Dept. Agric., Field Oper. Bur. Soils, 1902, 4th Rept., pp. 259–271, pls. 9–11, 1903.

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153 —— **Dorsey** (Clarence W.), **Mesmer** (Louis), and. Soil survey from Arecibo to Ponce, Porto Rico.

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154 —— **Mooney** (Charles N.) and. Soil survey of the Prince Edward area, Virginia.

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155 —— **Mooney** (Charles N.), Martin (J. O.) and. Soil survey of the Bedford area, Virginia.

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156 **Calkins** (Frank C.). Soils of the wheat lands of Washington.

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157 **Calvin** (Samuel). Artesian wells in Iowa.

Iowa State Institutions, Bull., vol. 4, pp. 402–408, 1902.

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158 —— Geology of Howard County [Iowa].

Iowa Geol. Surv., vol. 13, pp. 21–79, figs. 1–15, 1903.

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Iowa Geol. Surv., vol. 13, pp. 255–292, figs. 32–41, 1903.

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160 —— Geology of Mitchell County [Iowa].

Iowa Geol. Surv., vol. 13, pp. 293–338, figs. 42–53, 1903.

Describes physiographic features, the character, occurrence, and geologic relations of Devonian strata and Glacial deposits and the economic resources.

161 —— Physiography of Iowa.

Iowa Weather and Crop Service, Ann. Rept. for 1902, Appendix, pp. 3–11, 1 pl., 1903.

Describes topography and drainage. Includes an account of the distribution of the drift deposits and their relation to physiographic features.

162 **Camsell** (Charles). The region southwest of Fort Smith, Slave River, N. W. T.

Can. Geol. Surv., Summ. Rept. for 1902, pp. 149–167, 1903.

Contains observations on the geology of the region examined.

163 **Campbell** (H. D.) and **Howe** (James Lewis). A new (?) meteoric iron from Augusta Co., Virginia.

Am. Jour. Sci., 4th ser., vol. 15, pp. 469–471, 1 fig., 1903.

164 **Campbell** (Marius R.). Brownsville-Connellsville folio, Pennsylvania.

U. S. Geol. Surv., Geol. Atlas of U. S., folio no. 94, 1903.

Describes geographic, physiographic, and geologic relations to Appalachian province, surface features and drainage, physiographic history, geologic structure, character and occurrence of the Carboniferous strata and Quaternary deposits, character and occurrence of the coal beds and other economic resources. The section on natural gas is contributed by Myron L. Fuller.

165 —— Geographic development of northern Pennsylvania and southern New York.

Geol. Soc. Am., Bull., vol. 14, pp. 277–296, fig. 1, 1903.

Describes physiographic features of this region and discusses the mode and time of their origin.

166 —— Variation and equivalence of the Charleston sandstone.

Jour. Geol., vol. 11, pp. 459–468, 1903.

Reviews the divergent views as to the correlation of the sandstone of West Virginia, which the writer named the Charleston sandstone, with the Mahoning sandstone of Pennsylvania, and presents additional evidence for the author's view as to their distinctness.

167 —— Recent work in the bituminous coal field of Pennsylvania.

U. S. Geol. Surv., Bull. no. 213, pp. 270–275, 1903.

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168 **Campbell** (Marius R.). Borax deposits of eastern California.
U. S. Geol. Surv., Bull. no. 213, pp. 401–405, 1903.
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169 —— Basin-range structure in the Death Valley region of southeastern California.
Abstract: Science, new ser., vol. 17, p. 302, 1903; Sci. Am. Suppl., vol. 55, p. 22666, 1903; Am. Geol., vol. 31, pp. 311–312, 1903.

170 —— Pocono rocks in the Allegheny Valley.
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171 **Carmony** (F. A.). Jefferson County [Nebraska].
Nebr. Geol. Surv., vol. 1, pp. 235–241, figs. 157–166, 1903.
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172 **Carney** (Frank). A type case in diversion of drainage.
Jour. Geog., vol. 2, pp. 115–124, figs. 1–7, 1903.
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173 **Carter** (William T., jr.), **Smith** (William G.) and. Soil survey of the Smedes area, Mississippi.
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174 **Case** (E. C.). The osteology of Embolophorus dollovianus, Cope, with an attempted restoration.
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176 —— The structure and relationships of the American Pelycosauria.
Am. Nat., vol. 37, pp. 85–102, figs. 1–10, 1903.

177 **Casey** (Thomas L.). A new genus of Eocene Eulimidæ.
Nautilus, vol. 16, pp. 18–19, fig., 1902.

178 —— Notes on the Conrad collection of Vicksburg fossils, with descriptions of new species.
Phila. Acad. Nat. Sci., Proc., vol. 55, pp. 261–283, 1903.

179 **Catlett** (Charles). Geological relations of the manganese ore-deposits of Georgia. [In discussion of paper of Thomas L. Watson.]
Am. Inst. Mg. Engrs., Trans. (Albany meeting, February, 1903). 2 pp.
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180 **Chalmers** (Robert). Artesian borings, surface deposits, and ancient beaches in Ontario.
Can. Geol. Surv., Summ. Rept. for 1902, pp. 268–279, 1903.
Describes work upon surface deposits, exploration for natural gas and oil, determination of ancient shore lines of the Great Lakes, and the occurrence and utilization of peat.

181 **Chamberlin** (Thomas C.). The criteria requisite for the reference of relics to a glacial age.

Jour. Geol., vol. 11, pp. 64–85, fig. 1, 1903.

182 —— Distribution of the internal heat of the earth.

Abstract: Geol. Soc. Am., Bull., vol. 13, pp. 530–531, 1903.

Brief note on the character of the paper.

183 —— Has the rate of rotation of the earth changed appreciably during geological history?

Abstract: Geol. Soc. Am., Bull., vol. 13, p. 531, 1903.

Brief note on the theory of a high rate of terrestrial rotation in early geologic times.

184 —— The origin of ocean basins on the planetessimal hypothesis.

Abstract: Am. Geol., vol. 32, p. 14, 1903; Science, new ser., vol. 17, pp. 300–301, 1903.

185 **Church** (John A.). The Tombstone, Arizona, mining district.

Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 3–37, figs. 1–12, 1903.

Describes the character and occurrence of sedimentary strata, the geologic structure, the character and occurrence of eruptive rocks, and the position and relations of the ore bodies of gold, silver, and manganese.

186 —— [In discussion of paper by Walter P. Jenney, "The chemistry of ore-deposition."]

Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 1065–1070, 1903.

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187 **Cirkel** (Fritz). Vorkommen und Gewinnung von Asbest in Canada.

Zeitsch. f. prak. Geol., vol. 11, pp. 123–131, figs. 33–35, 1903.

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188 **Clapp** (F. G.), **Fuller** (M. L.) and. Marl-loess of the lower Wabash valley.

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189 **Clark** (P. Edwin), **Van Ingen** (Gilbert) and. Disturbed fossiliferous rocks in the vicinity of Rondout, N. Y.

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190 **Clark** (W. B.). The Cretaceous-Eocene boundary in the Atlantic coastal plain.

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191 **Clarke** (C. H.). Notes on the Michipicoten gold-belt.

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192 **Clarke** (Frank Wigglesworth). Mineral analyses from the laboratories of the United States Geological Survey, 1880 to 1903, tabulated by F. W. Clarke, Chief Chemist.

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194 —— The composition of glauconite and greenalite.
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195 **Clarke** (John Mason). Report of the State paleontologist, 1902.
N. Y. State Mus., Bull. 69, pp. 851–891, 1903.
Gives a review of the work of the office of the State paleontologist of New York for the year 1901–2.

196 —— Mastodons of New York.
N. Y. State Mus., Bull. 69, pp. 921–933, pls. 1–2, 1903.
Describes occurrences of mastodon remains in the State of New York.

197 —— Construction of the Olean rock section.
N. Y. State Mus., Bull. 69, pp. 996–999, 1903.
Discusses the discrepancy of results obtained by stratigraphic and paleontologic work in the Olean quadrangle of New York and the geologic position of the Cattaraugus beds.

198 —— Torsion of the lamellibranch shell, an illustration of Noetling's law.
N. Y. State Mus., Bull. 69, pp. 1228–1233, figs. 1–7, 1903.

199 —— Some Devonic worms.
N. Y. State Mus., Bull. 69, pp. 1234–1238, pls. 37–38, 1903.

200 —— Naples fauna in western New York.
N. Y. State Mus., Mem. 6, pp. 199–454, pls. A–F, 1–20, figs. 1–16, 1903.
Discusses conditions of sedimentation and the distribution of land and water prevailing in the area of western New York in later Devonian times, and the stratigraphy of the Portage and character of the fauna, and gives systematic descriptions of the species and tables of distribution and comparison with faunas of other regions.

201 —— Classification of New York series of geologic formations.
N. Y. State Mus., Handbook 19, 28 pp., 1903.
Discusses the nomenclature and classification of the New York series of geologic formations. Includes a table showing the geologic position and geographic distribution of formations in the State of New York.

202 —— Origin of the limestone faunas of the Marcellus shales of New York.
Abstract: Geol. Soc. Am., Bull., vol. 13, p. 535, 1903.

203 —— (assisted by Ruedemann, Rudolph). Catalogue of type specimens of Paleozoic fossils in New York State Museum.
N. Y. State Mus., Bull. 65, 847 pp., 1903.

204 —— and **Ruedemann** (Rudolf). Guelph fauna in the State of New York.
N. Y. State Mus., Mem. 5, 195 pp., 21 pls., 1903.
Describes stratigraphy, occurrence, and geologic relations of the Guelph formation in New York, gives systematic descriptions of the fauna, and discusses the conditions of life and sedimentation during the prevalence of the Guelph fauna and its distribution.

205 **Clarke** (John Mason). See Ruedemann (Rudolf), 1044.

206 **Claypole** (Edward W.). The Devonian era in the Ohio basin.

Am. Geol., vol. 32, pp. 15–41, pls. 4–10, pp. 79–105, pls. 16–18, pp. 240–250, 312–322, 335–353, 1903.

Discusses occurrence, lithologic, stratigraphic, and faunal features of Devonian formations in the Ohio basin, geographic and hypsographic conditions prevailing in Devonian times, and geologic and geographic distribution of the invertebrate and vertebrate faunas, and describes briefly species of Cladodus and Monocladodus.

207 **Cleland** (Herdman Fitzgerald). A study of the Hamilton formation of the Cayuga Lake section in central New York.

U. S. Geol. Surv., Bull. no. 206, 112 pp., 5 pls., 3 figs., 1903.

Describes the general geology of the Cayuga Lake region in New York and the history, correlation, and faunal zones of the Hamilton formation in this region, and gives a classified list of species found, with notes on their occurrence, general observations and conclusions, and a table showing vertical distribution and relative abundance of Hamilton species.

208 —— Further notes on the Calciferous (Beekmantown) formation of the Mohawk Valley, with descriptions of new species.

Am. Pal., Bull. no. 18, pp. 31–50, pls. 1–4, 1903.

Describes character, occurrence, and fossil contents of Calciferous strata in the Mohawk Valley, and gives detailed descriptions of the new species of fossils.

209 **Clements** (J. Morgan). The Vermilion iron-bearing district of Minnesota.

U. S. Geol. Surv., Mon., vol. 45, 463 pp., 13 pls., 23 figs., with an atlas of 26 sheets, 1903.

Reviews the literature regarding the district, describes its physiography, the character, occurrence, and relations of the Archæan, Huronian, and Keweenawan rocks and drift, and the occurrence, character, and origin of the ore deposits.

210 —— Ellipsoidal structure in pre-Cambrian rocks of Lake Superior region.

Abstract: Geol. Soc. Am., Bull., vol. 14, p. 8, 1903.

211 —— Vermilion district of Minnesota.

Abstract: Geol. Soc. Am., Bull., vol. 14, p. 9, 1903.

Gives a brief outline of the geology.

212 **Cobb** (Collier). Origin of the sandhill topography of the Carolinas.

Abstract: Science, new ser., vol. 17, pp. 226–227, 1903; Sci. Am. Suppl., vol. 55, p. 22666, 1903.

213 —— Recent changes in the North Carolina coast, with special reference to Hatteras Island.

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214 **Cockerell** (T. D. A.). A new fossil Ashmunella.
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215 **Coffey** (George N.) and **Hearn** (W. Edward). Soil survey of Alamance County, North Carolina.
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U. S. Dept. Agric., Field Oper. Bur. Soils, 1901, 3d Rept., pp. 311–315, pl. 35, 1902.
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17 —— and party. Soil survey of St. Clair County, Illinois.
U. S. Dept. Agric., Field Oper. Bur. Soils, 1902, 4th Rept., pp. 507–532, pls. 27–28, 1903.
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18 —— and party. Soil survey of Clay County, Illinois.
U. S. Dept. Agric., Field Oper. Bur. Soils, 1902, 4th Rept., pp. 533–548, pl. 29, 1903.
Includes a brief account of the physiography and geology.

19 —— **Dorsey** (Clarence W.) and. Soil survey of Montgomery County, Ohio.
See Dorsey (C. W.) and Coffey (G. N.), 312.

20 **Cohen** (E.). Über ein neues Meteoreisen von Locust Grove, Henry Co., Nord-Carolina, Vereinigte Staaten.
Preus. Akad. d. Wissen. zu Berlin, Sitzungsb., pp. 76–81, 1897.
Describes the character and constitution of this meteorite.

21 —— Das Meteoreisen von Forsyth Co., Georgia, Vereinigte Staaten.
Preus. Akad. d. Wissen. zu Berlin, Sitzungsb., pp. 386–396, figs. 1–2, 1897.
Describes the occurence, characters, and constitution of this meteorite from Forsyth County, Georgia.

22 —— Über das Meteoreisen von Cincinnati, Vereinigte Staaten.
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Describes the characters and constitution of this meteorite.

23 **Cole** (Leon J.). The delta of the St. Clair River.
Mich. Geol. Surv., vol. 9, pt. 1, pp. 1–28, pls. 1–4, 1903.

24 **Coleman** (A. P.). The classification of the Archæan.
Can. Roy. Soc., Proc. & Trans., 2d ser., vol. 8, sect. 4, pp. 135–148, 1902.
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225 **Coleman** (A. P.). The Sudbury [Ontario] nickel deposits.
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226 —— Types of iron-bearing rocks in Ontario.
Eng. & Mg. Jour., vol. 75, pp. 294–295, 1903.

227 **Collie** (George Lucius). Physiography of Wisconsin.
Am. Bur. Geog., Bull., vol. 2, pp. 270–287, 9 figs., 1901.

228 —— Ordovician section near Bellefonte, Pennsylvania.
Geol. Soc. Am., Bull., vol. 14, pp. 407–420, pl. 59, 1903.
Describes position, character, stratigraphy, and fauna of Ordovician formations in Center County, Pennsylvania, and describes some new species of Ordovician fossils.

229 **Collier** (Arthur J.). The coal resources of the Yukon, Alaska.
U. S. Geol. Surv., Bull. no. 218, 71 pp., 6 pls., 3 figs., 1903.
Describes the general geology and the occurrence and character of the coal deposits along the Yukon River.

230 —— The Glenn Creek gold mining district, Alaska.
U. S. Geol. Surv., Bull. no. 213, pp. 49–56, 1903.
Describes placer deposits and developments in this region.

231 —— Coal resources of the Yukon Basin, Alaska.
U. S. Geol. Surv., Bull. no. 213, pp. 276–284, 1903.
Describes the occurrence of coal and gives notes on the character of the coals and the mining developments.

232 —— Tin in the York region, Alaska.
Eng. & Mg. Jour., vol. 76, pp. 999–1000, ill., 1903.
Describes the occurrence of deposits of tin ore.

233 —— Coal-bearing series of the Yukon.
Abstract: Science, new ser., vol. 17, p. 668, 1903.
Discusses the geologic age of the coal-bearing formations.

234 **Collins** (G. E.). Vein-structure at the Reynolds mine, Georgia.
Inst. Mg. & Met., Trans., vol. 9, pp. 365–371, pls. 12–16, 1901.
Discusses the vein phenomena in the auriferous crystalline rocks of the region.

235 **Comstock** (Frank M.) A small esker in western New York.
Am. Geol., vol. 32, pp. 12–14, figs. 1–3, 1903.

236 **Comstock** (Theodore B.). Memoir of Edward Waller Claypole.
Geol. Soc. Am., Bull., vol. 13, pp. 487–497, 1903.
Includes a list of publications.

237 **Concannon** (Michael). Relation [regarding the discovery of the Lansing, Kansas, skeleton.]
Memoirs of Exploration in the Basin of the Mississippi, vol. 7, Kansas, pp. 92–93, 1903.
Details the circumstances of the finding of the fossil human remains near Lansing, Kansas.

238 **Condra** (George Evart). The Coal Measure bryozoa of Nebraska.
Nebr. Geol. Surv., vol. 2, pt. 1, pp. 11–168, pls. 1–21, 1903.
Reviews literature bearing on the subject, gives list of Coal Measure bryozoa in the United States, table of geographic distribution in Nebraska, and systematic descriptions of genera and species.

239 —— On Rhombopora lepidodendroides Meek.
Am. Geol., vol. 31, pp. 22–24, pl. 2, 1903.
Describes characters and occurrence in the Permian of Nebraska.

240 —— An old Platte channel [Nebraska].
Am. Geol., vol. 31, pp. 361–369, figs. 1–2, 1903.
Describes situation, stratigraphic and physiographic features of the valley to which the name Todd Valley is given, and the evidences of its containing a buried channel formerly occupied by the Platte River.

241 **Coste** (Eugene). Volcanic origin of natural gas and petroleum.
Eng. & Mg. Jour., vol. 75, p. 439, 1903.
Abstract from paper read before the Can. Mg. Inst., March, 1903.

242 **Cowles** (Henry C.). The influence of underlying rocks on the character of the vegetation.
Am. Bur. Geog., Bull., vol. 2, pp. 163–176, 376–388, figs. 1–10, 1901.

243 **Crane** (W. R.). Asphalt refining. Methods employed in the Tar Springs Asphalt Co.'s refinery, near Comanche, Ind. T.
Mines & Minerals, vol. 23, pp. 337–341, figs. 1–4, 1903.
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244 —— Coal fields of Kansas. Recent discoveries and developments in the Cretaceous formation in the northern central portion of the State.
Mines & Minerals, vol. 24, p. 94, 1 fig., 1903.
Describes the occurrence of a workable coal seam and gives a section of the strata penetrated by a shaft.

245 —— Coal mining in the Indian Territory—the southwestern field.
Eng. & Mg. Jour., vol. 76, pp. 577–581, figs. 1–7, 1903.
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246 **Crevecœur** (F. F.). List of fossil plants collected in the vicinity of Onaga, Kans.
Kans. Acad. Sci., Trans., vol. 18, pp. 124–128, 3 figs., 1903.
Describes the stratigraphy and occurrence of fossils at this locality.

247 **Crosby** (William O.). The hanging valleys of Georgetown, Colorado.
Am. Geol., vol. 32, pp. 42–48, pls. 11–13, 1903; Tech. Quart., vol. 16, pp. 41–50, figs. 1–4, 1903.
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248 **Crosby** (William O.). A study of the geology of the Charles River estuary and Boston Harbor, with special reference to the building of the proposed dam across the tidal portion of the river.

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Describes the geologic formations of the vicinity, the bedded rock and glacial deposits, and the processes and conditions of sedimentation prevailing now and in the recent past.

249 —— Structure and composition of the delta plains formed during the Clinton stage in the Glacial lake of the Nashua Valley.

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250 **Cross** (Whitman). Observations on Hawaiian geology.

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251 —— **Iddings** (Joseph P.), **Pirsson** (Louis V.), **Washington** (Henry S.). Quantitative classification of igneous rocks based on chemical and mineral characters, with a systematic nomenclature.

University of Chicago Press, 286 pp., 1903.

A review of the development of systematic petrography in the nineteenth century, by Whitman Cross, is followed by a discussion of the principles of classification of igneous rocks and an exposition of the new system of classification and nomenclature proposed by the authors and methods of calculation for determining the position of a rock in their system of classification.

252 **Crowther** (Henry M.). The copper deposits of the Beaver River Range, Utah.

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253 **Culbertson** (Glenn). Ripple marks in Hudson limestone of Jefferson County, Indiana.

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254 **Cumings** (Edgar Roscoe). The morphogenesis of Platystrophia; a study of the evolution of a Paleozoic brachiopod.

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256 —— Note on the West Indian eruptions of 1902.

Am. Geol., vol. 31, pp. 40–43, 1903.

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257 —— Modern rational relief of the earth's surface.

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259 —— Petrography and age of the Northumberland rock.
N. Y. State Mus., 55th Ann. Rept., pp. r24–r29, 1903.
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260 **Dale** (T. Nelson). The slate industry at Slatington, Pa., and Martinsburg, W. Va.
U. S. Geol. Surv., Bull. no. 213, pp. 361–364, 1903.
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261 **Dall** (William Healey). Contributions to the Tertiary fauna of Florida, with especial reference to the silex beds of Tampa and the Pliocene beds of the Caloosahatchie River, including a complete revision of the generic groups treated of and their American Tertiary species. Part VI. Concluding the work.
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262 —— The Grand Gulf formation.
Science, new ser., vol. 18, pp. 83–85, 1903.
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263 —— See Diller (J. S.), 302.

264 —— See Arnold (Ralph), 38.

265 **Daly** (Reginald Aldworth). The geology of Ascutney Mountain, Vermont.
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266 —— The mechanics of igneous intrusion.
Am. Jour. Sci., 4th ser., vol. 15, pp. 269–298; vol. 16, pp. 107–126, figs. 1–3, 1903.
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267 —— Variolitic pillow lava from Newfoundland.
Am. Geol., vol. 32, pp. 65–78, pls. 14–15, figs. 1–3, 1903.
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268 **Daly** (Reginald Aldworth). Geology of the western part of the international boundary (49th parallel).

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269 —— Report on geology. In report of the Brown-Harvard expedition to Nachvak, Labrador, in the year 1900.

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270 **Darton** (Nelson Horatio). Preliminary report on the geology and water resources of Nebraska west of the one hundred and third meridian.

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271 —— Camp Clarke folio, Nebraska.

U. S. Geol. Surv., Geol. Atlas of U. S., folio no. 87, 1903.

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272 —— Scotts Bluff folio, Nebraska.

U. S. Geol. Surv., Geol. Atlas of U. S., folio no. 88, 1903.

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273 —— Some relations of Tertiary formations of the northern Great Plains.

Abstract: Science, new ser., vol. 17, p. 218, 1903.

274 —— Comparison of stratigraphy of the Big Horn Mountains, Black Hills, and Rocky Mountain Front Range.

Abstract: Science, new ser., vol. 17, p. 292, 1903.

275 **Davis** (C. A.). A contribution to the natural history of marl.

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276 **Davis** (William Morris). Current notes on physiography.

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277 —— Current notes on physiography.

Science, new ser., vol. 17, pp. 193–195, 1903.

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279 —— Current notes on physiography.
Science, new ser., vol. 17, pp. 434–435, 1903.
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280 —— Current notes on physiography.
Science, new ser., vol. 17, pp. 550–552, 1903.
Contains observations on the physiography of the southern Appalachian region.

281 —— Current notes on physiography.
Science, new ser., vol. 17, pp. 672–673, 1903.
Discusses physiographic features of the Snake River lava plains in Idaho.

282 ——An excursion to the plateau province of Utah and Arizona.
Harvard Coll., Mus. Comp. Zool., Bull., vol. 42, pp. 1–50, pls. 1–7, figs. 1–14, 1903.
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283 —— The mountain ranges of the Great Basin.
Harvard Coll., Mus. Comp. Zool., Bull., vol. 42, pp. 129–177, pls. 1–7, figs. 1–18, 1903.
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284 —— The development of river meanders.
Geol. Mag., new ser., dec. 4, vol. 10, 1903.

285 —— The stream contest along the Blue Ridge.
Phila. Geog. Soc., Bull., vol. 3, pp. 213–244, pls. 1–4, 1903.
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286 —— Effect of shore line on waves.
Abstract: Geol. Soc. Am., Bull., vol. 13, p. 528, 1903.

287 —— Walls of the Colorado Canyon.
Abstract: Geol. Soc. Am., Bull., vol. 13, p. 528, 1903.
Contains brief notes.

288 —— The fresh-water Tertiaries at Green River, Wyoming.
Abstract: Science, new ser., vol. 17, pp. 220–221, 1903.

289 —— Block mountains of the Basin Range province.
Abstract: Science, new ser., vol. 17, p. 301, 1903; Eng. & Mg. Jour., vol. 75, p. 153, 1903.
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290 **Day** (David T.). Experiments on the diffusion of crude petroleum through fuller's earth.
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291 **Day** (David T.). [In discussion of paper by George I. Adams, "Principles controlling the geologic deposition of the hydrocarbons."]

Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 1053–1055, 1903.

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292 **Dean** (Bashford). The early development of sharks from a comparative standpoint.

Abstract: N. Y. Acad. Sci., Ann., vol. 15, pp. 45–46, 1903.

293 **Deckert** (Emil). Die Erdbebenherde und Schüttergebiete von Nord-Amerika in ihren Beziehungen zu den morphologischen Verhältnissen.

Berlin Ges. für Erdkunde, Zeitsch., 1902, no. 5, pp. 367–389, 1902.

A general discussion of the occurrences of earthquakes in North America with reference to their morphological relationships.

294 **De Cou** (Ralph E.), **Downer** (R. H.) and. A description of the working mines of Ouray County, Colorado.

See Downer (R. H.) and De Cou (R. E.), 322.

295 **Dennis** (W. B.). The quicksilver deposits of Oregon.

Eng. & Mg. Jour., vol. 76, pp. 539–541, 1903.

Describes the occurrence, character, and geologic relations of the quicksilver ore deposits of Oregon and the mining developments.

296 **Dickinson** (Harold T.). Quarries of bluestone and other sandstones in the upper Devonian of New York State.

N. Y. State Museum, Bull. 61, 112 pp., 20 pls., 1903.

Describes the character, occurrence, and quarrying.

297 **Dickson** (Charles William). The ore deposits of Sudbury, Ontario.

Columbia Univ., Contr. from Geol. Dept., vol. 11, no. 91, 65 pp., figs. 1–26, 1903; Am. Inst. Mg. Engrs, Trans. (Albany meeting, February, 1903), 65 pp.

Contains a discussion of the origin of the Sudbury nickeliferous ores. Includes a bibliography of the subject.

298 —— Note on the condition of platinum in the nickel-copper ores from Sudbury [Ontario].

Am. Jour. Sci., 4th ser., vol. 15, pp. 137–139, 1903.

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299 **Diller** (Joseph Silas). The Klamath Mountains.

Mazama, vol. 1, no. 1, pp. 104–108, 1896.

Describes briefly the geologic history of the Klamath Mountains region.

300 —— The geology of Crater Lake.

Mazama, vol. 1, no. 2, pp. 161–170, pls. 20–23, 1897.

Describes geologic structure and history of Crater Lake on Mount Mazama, Oregon.

301 **Diller** (Joseph Silas). Port Orford folio, Oregon.
U. S. Geol. Surv., Geol. Atlas of U. S., folio no. 89, 1903.
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302 —— Klamath Mountains section, California.
Am. Jour. Sci., 4th ser., vol. 15, pp. 342–362, 1903.
Describes general distribution and structural relations of Paleozoic, Mesozoic, and Cenozoic formations of the Klamath Mountains and occurrence and characters of eruptive rocks. Contains reports on fossils by Charles Schuchert, George H. Girty. Wm. M. Fontaine, David White, F. H. Knowlton, T. W. Stanton, and W. H. Dall.

303 —— Copper deposits of the Redding region, California.
U. S. Geol. Surv., Bull. no. 213, pp. 123–132, 1903.
Describes sedimentary and igneous rocks of the region and their geologic relations and character and occurrence of the ore deposits.

304 —— Iron ores of the Redding quadrangle, California.
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305 —— Limestone of the Redding district, California.
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306 **Divers** (Edward). Suggested nature of the phenomena of the eruption of Mont Pelée on July 9. Observed by the Royal Society Commission.
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307 **Dixon** (J. D.), **Nolan** (A. W.) and. Geology of St. Helen's Island [Quebec].
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308 **Dodge** (Richard E.). An interesting landslide in the Chaco Cañon, New Mexico.
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309 —— Arroyo formation.
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310 **Dorsey** (Clarence W.) and **Bonsteel** (J. A.). Soil survey in the Connecticut Valley.
U. S. Dept. Agric., Field Oper. Div. Soils, 1899, pp. 125–140, pls. 21–27, 1900.
Includes a brief account of the geology and topographic features.

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U. S. Dept. Agric., Field Oper. Div. Soils, 1900, 2d Rept., pp. 61–84, pls. 1–4, 1901.
Includes a brief account of the topography and geology.

312 **Dorsey** (Clarence W.) and **Coffey** (George N.). Soil survey of Montgomery County, Ohio.

U. S. Dept. Agric., Field Oper. Div. Soils, 1900, 2d Rept., pp. 85–102, pls. 5–7, 1901.

Includes a short account of the geology and physiography.

313 —— and **Bonsteel** (Jay A.). Soil survey of Cecil County, Md.

U. S. Dept. Agric., Field Oper. Div. Soils, 1900, 2d Rept., pp. 103–124, 1901.

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314 —— and party. Soil survey of the Statesville area, North Carolina.

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315 —— **Mesmer** (Louis) and **Caine** (Thomas A.). Soil survey from Arecibo to Ponce, Porto Rico.

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316 **Douglass** (Earl). Astropecten? montanus—a new star-fish from the Fort Benton; and some geological notes.

Carnegie Mus., Ann., vol. 2, pp. 5–8, fig. 1, 1903.

317 —— New vertebrates from the Montana Tertiary.

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A brief account of the stratigraphy of the formations from which the fossils were obtained precedes detailed generic and specific descriptions.

318 **Dowlen** (Walton E.). The Turtle Mountain rock slide [Alberta, Canada].

Eng. & Mg. Jour., vol. 76, pp. 10–12, ill., 1903.

Describes a rock slide and the geologic conditions which produced it.

319 **Dowling** (D. B.). Eastern Assiniboia and southern Manitoba.

Can. Geol. Surv., Summ. Rept. for 1902, pp. 180–190, 1903.

Describes observations upon the geology and economic resources of the region examined.

320 —— Notes to accompany a contoured plan of the lower slope of Turtle Mountain, Manitoba.

Can. Geol. Surv., Summ. Rept. for 1902, pp. 191–201, 1903.

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321 **Downer** (R. H.). Ore deposits of the American-Nettie mine, Ouray, Colo.

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Colo. Sch. Mines, Bull., vol. 1, pp. 242–259, 1901.
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323 **Drake** (N. F.), **Lindgren** (Waldemar) and. Silver City folio—Idaho.
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324 **Dresser** (John A.). On the physical geography of a northern section of the Appalachian mountain system.
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325 —— An investigation of the copper-bearing rocks of the eastern townships, Province of Quebec.
Can. Geol. Surv., Summ. Rept. for 1902, pp. 302–316, 1903.
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326 **Dryer** (Charles R.). The use of the word "geest" in geology.
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327 **Duerden** (J. E.). A method of studying the septal sequence in Paleozoic corals.
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328 —— The morphology of the Madreporaria.
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329 **Dumble** (Edwin T.). Physical geography, geology, and resources of Texas.
A Comprehensive History of Texas, published by W. G. Scarff, Dallas, Tex., vol. 2, chap. 4, pp. 471–516, ill., 1898.
Includes a brief account of the geologic history and structure of the State, and describes geographic and physiographic features and mineral resources.

330 —— Geology of the Beaumont oil field.
Houston Post, 5 pp., 1901. (Private publication.)
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331 —— The iron ores of east Texas.
Houston Post, 4 pp., 1901. (Private publication.)
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332 —— Geology of southwestern Texas.
Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 913–987, figs. 1–2, 1903.
Describes the topography, and the character, occurrence, and geologic relations of formations of Tertiary and Pleistocene age in southwestern Texas.

333 **Duryee** (Edward). Cement investigations in Arizona.
U. S. Geol. Surv., Bull. no. 213, pp. 372–380, 1903.

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334 **Eakle** (Arthur S.). Note on the identity of palacheite and botryogen.

Am. Jour. Sci. 4th ser., vol. 16, pp. 379–380, 1903.

Describes composition, characters, and occurrence.

335 —— Palacheite.

Cal. Univ., Dept. Geol., Bull., vol. 3, pp. 231–236, pl. 20, 1903.

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336 **Easter** (S. E.). Jade.

Nat. Geog. Mag., vol. 14, pp. 9–17, 1903.

Describes characters, occurences, and uses.

337 **Eastman** (Charles R.). Carboniferous fishes from the central Western States.

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A short account of the stratigraphy of the Upper Carboniferous of Kansas and Nebraska precedes the systematic descriptions.

338 —— A peculiar modification amongst Permian dipnoans.

Am. Nat., vol. 37, pp. 493–495, figs. 1–2, 1903.

339 —— Devonian fish fauna of Iowa.

Abstract: Geol. Soc. Am. Bull., vol. 13, p. 537, 1903.

340 **Eaton** (G. F.). Notes on the collection of Triassic fishes at Yale.

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341 —— The characters of Pteranodon.

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343 —— Summaries of the literature of structural materials. III.

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344 —— Summaries of the literature of economic geology.

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346 —— Molding sand: its uses, properties, and occurrence.

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347 **Eckel** (Edwin C.). The Dahlonega gold district of Georgia.
Eng. & Mg. Jour., vol. 75, pp. 219–220, 1903.
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U. S. Geol. Surv., Bull. no. 213, pp. 57–63, 1903; Mines & Minerals, vol. 23, pp. 493–494, 1903.
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349 —— Utilization of iron and steel slags.
U. S. Geol. Surv., Bull. no. 213, pp. 221–231, 1903.

350 —— Stoneware and brick clays of western Tennessee and northwestern Mississippi.
U. S. Geol. Surv., Bull. no. 213, pp. 382–391, 1903.
Describes occurrence, character, and utilization of clay deposits in this region.

351 —— Salt and gypsum deposits of southwestern Virginia.
U. S. Geol. Surv., Bull. no. 213, pp. 406–416, 1903.
Describes briefly the stratigraphy and geologic structure of the region, and the occurrence of salt and gypsum deposits and their development.

352 —— The white phosphates of Decatur County, Tenn.
U. S. Geol. Surv., Bull. no. 213, pp. 424–425, 1903.
Describes occurrence of phosphate deposits in this area.

353 —— Dahlonega mining district, Georgia.
Abstract: Science, new ser., vol. 17, p. 793, 1903.
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354 —— **Hayes** (C. W.) and. Iron ores of the Cartersville district, Georgia.
See Hayes (C. W.) and Eckel (E. C.), 529.

355 —— **Hayes** (C. W.) and. Occurrence and development of ocher deposits in the Cartersville district, Georgia.
See Hayes (C. W.) and Eckel (E. C.), 530.

356 **Eisele** (Martin A.). Report of the superintendent of the Hot Springs Reservation.
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Gives chemical analyses of the water and a brief extract from W. H. Weed's report as to the source of the heat.

357 **Eisen** (Gustav.). The earthquake and volcanic eruption in Guatemala in 1902.
Am. Geog. Soc., Bull., vol. 35, pp. 325–352, 4 figs., 1903.
Describes the earthquake of April, 1902, and its effects, the volcanoes and their eruptions, more particularly that of Santa Maria of Oct. 24, 1902, the character of the ejected material and the physiographic changes produced.

358 **Eldridge** (George H.). Origin and distribution of asphalt and bituminous rock deposits in the United States.

U. S. Geol. Surv., Bull. no. 213, pp. 296–305, 1903.

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359 —— The petroleum fields of California.

U. S. Geol. Surv., Bull. no. 213, pp. 306–321, 1903.

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360 **Elftman** (A. H.). The Highland range in Minnesota.

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361 —— Keewatin and Laurentide ice-sheets in Minnesota.

Abstract: Geol. Soc. Am., Bull., vol. 13, pp. 536–537, 1903.

Notes on the ice invasion.

362 **Ellis** (Mary). Index to publications of the New York State Natural History Survey and New York State Museum 1837–1902; also including other New York publications on related subjects.

N. Y. State Mus., Bull. 66, 653 pp., 1903.

Includes a list of the publications, an alphabetic author and subject index, and an index to descriptions of genera and species of fossils, compiled under the direction of John M. Clarke, State paleontologist.

363 **Ells** (R. W.). The progress of geological investigation in Nova Scotia.

Nova Scotian Inst. Sci., Proc. & Trans., vol. 10, pp. 433–446, 1903.

364 —— The oil fields of Gaspé [Quebec].

Can. Geol. Surv., Summ. Rept. for 1902, pp. 338–361, 1903.

Describes the geologic structure of the field, the conditions requisite for oil production, and the explorations for oil.

365 —— The Albert shale deposits of Albert and Westmorland Counties, New Brunswick.

Can. Geol. Surv., Summ. Rept. for 1902, pp. 361–367, 1903.

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366 —— Report on the geology of Prince Edward Island with reference to proposed borings for coal.

Can. Geol. Surv., Summ. Rept. for 1902, pp. 367–377, 1903.

367 —— Notes on some interesting rock-contacts in the Kingston district, Ontario.

Can. Roy. Soc., Proc. & Trans., 2d ser., vol. 9, sect. 4, pp. 97–108, 1903.

Describes observations upon the character, occurrence, and geologic relations of formations of Cambrian and Ordovician age in Quebec and Ontario.

368 **Elrod** (Morton John). The physiography of the Flathead Lake region [Montana].

Mont. Univ., Bull. no. 16 (?), pp. 197–203, ill., 1903.

369 **Emerson** (Benjamin K.). Glacial cirques and rock-terraces on Mount Toby, Massachusetts.
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370 —— A plumose diabase containing sideromelan and spherulites of calcite and blue quartz.
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371 —— **Perry** (Joseph H.) and. The geology of Worcester, Massachusetts.
See Perry (J. H.) and Emerson (B. K.), 971.

372 **Emmons** (Samuel Franklin). The Little Cottonwood granite body of the Wasatch Mountains.
Am. Jour. Sci., 4th ser., vol. 16, pp. 139–147, 1 fig., 1903.
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373 —— **Hayes** (C. W.), Geologists in charge. Contributions to economic geology, 1902.
U. S. Geol. Surv., Bull. no. 213, 449 pp., 1903.
Contains reports by different members of the staff of the U. S. Geological Survey of the economic results of investigations made by the Geological Survey, and bibliographies of the subjects treated.

374 —— Investigation of metalliferous ores.
U. S. Geol. Surv., Bull. no. 213, pp. 15–28, 1903.
Describes the character and scope of the economic work of the U. S. Geological Survey, gives brief outlines of economic publications on metalliferous deposits by the Survey during 1901, and enumerates by geographic areas the work in hand.

375 —— Platinum in copper ores in Wyoming.
U. S. Geol. Surv., Bull. no. 213, pp. 94–97, 1903.
Gives a brief account of the topography and geology of the Medicine Bow Range in Wyoming and the occurrence of platinum in the copper ores of the New Rambler mine.

376 —— [In discussion of paper by W. P. Jenney, "The mineral crest, or the hydrostatic level attained by the ore-depositing solutions in certain mining districts of the Great Salt Lake Basin."]
Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 1062–1063, 1903.

377 —— The drainage of the valley of Mexico.
Abstract: Science, new ser., vol. 17, p. 309, 1903.

378 —— Genetic classification of ore deposits.
Abstract: Science, new ser., vol. 17, pp. 541–542, 1903.

379 **Evans** (H. F.). Canadian geology.
Mg. & Sci. Press, vol. 86, pp. 299–300, 1903.
Gives a general account of the geology of Canada.

380 **Evans** (H. F.). The Adams Lake series, British Columbia.
Mg. & Sci. Press, vol. 86, pp. 348–349, 1903.
Describes the occurrence of this formation and the strata associated with it, and discusses its geologic relations and age.

381 **Evans** (Nevil Norton). Native arsenic from Montreal.
Am. Jour. Sci., 4th ser., vol. 15, pp. 92–93, 1903.

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382 **Fairbanks** (Harold W.). The physiography of California.
Am. Bur. Geog., Bull., vol. 2, pp. 232–252, 329–353, 10 figs., 1901.

383 —— The physiography of southern Arizona and New Mexico.
Abstract: Eng. & Mg. Jour., vol. 75, p. 154, 1903; Jour. Geol., vol. 11, pp. 97–99, 1903.

384 **Fairchild** (Herman Le Roy). Elements of geology: a text-book for colleges and the general reader by Joseph Le Conte. Revised and partly rewritten by Herman Le Roy Fairchild.
See Le Conte (Joseph), 781.

385 —— Latest and lowest pre-Iroquois channels between Syracuse and Rome.
N. Y. State Mus., 55th Ann. Rept., pp. r31–r47, pls. 7–31, 1903.
Describes the occurrence and formation of river channels formed during the Glacial period in central New York.

386 **Fall** (Delos). Marls and clays in Michigan.
Mich. Geol. Surv., vol. 8, pt. 3, pp. 343–353, 1903.
Discusses occurrence, composition, and character of marls and clays in Michigan with especial reference to their use in the manufacture of Portland cement.

387 **Faribault** (E. Rodolphe). Nova Scotia gold fields.
Can. Geol. Surv., Summ. Rept. for 1902, pp. 399–427, 1903.
Describes geologic investigations made in the gold-producing districts of Nova Scotia.

388 **Farrington** (Oliver Cummings). Catalogue of the collection of meteorites, May 1, 1903.
Field Col. Mus., Geol. ser., vol. 2, pp. 79–124, pls. 30–39, 1903.
The alphabetic list of meteorites includes notes on the character and source of the specimens, some of which are figured.

389 —— An occurrence of free phosphorus in the Saline Township meteorite.
Am. Jour. Sci., 4th ser., vol. 15, pp. 71–72, 1903.

390 —— Meteorites of northwestern Kansas.
Abstract: Geol. Soc. Am., Bull., vol. 14, p. 6, 1903.

391 **Felix** (J.). Geologiai úti vázlatok észak-amerikából. Geologische Reiseskizzen aus Nord-amerika.

Földtani Közlöny, vol. 25, pp. 5–29, 69–94, pl. 1 and 1 fig., 1895.

Gives observations of a geological nature made during a tour through the United States and Canada, particularly upon the glaciers and petrography of the Cascade Mountains.

392 **Fenneman** (N. M.). The Boulder, Colo., oil field.

U. S. Geol. Surv., Bull. no. 213, pp. 322–332, 1903.

Describes location, general geologic structure and development of the field, the character and occurrence of the oil-bearing strata and the production of oil.

393 **Fernie** (W. Blakemore). The Frank disaster [Alberta].

Can. Mg. Rev., vol. 22, pp. 121–122, 1903.

Discusses the cause of the landslide.

394 **Finlay** (George Irving). Geology of the San Pedro district, San Luis Potosi, Mexico.

School of Mines Quart., vol. 25, pp. 60–69, ill., 1903; Columbia Univ., Dept. Geol., Contr., vol. 12, no. 101, 1903.

Describes the general geology of the region, the character and occurrence of the rocks and ore deposits, chiefly gold, silver, and lead, and discusses the origin of the latter.

395 —— Geological observations along the northern boundary of Montana.

Abstract: N. Y. Acad. Sci., Ann., vol. 15, pp. 68–69, 1903.

396 —— The geology of the nephelite syenite area at San José, Tamaulipas, Mexico.

Abstract: Am. Geol., vol. 32, pp. 63–64, 1903; Science, new ser., vol. 18, pp. 17–18, 1903.

397 —— and **Kemp** (J. F.). The nephelite syenite area of San Jose, Tamaulipas, Mexico.

Abstract: Science, new ser., vol. 17, p. 295, 1903.

398 **Finlay** (J. R.). The mining industry of the Cœur d'Alenes, Idaho.

Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 235–271, figs. 1–21, 1903.

Describes the geologic structure of the region, the occurrence and character of the veins and ore deposits, chiefly lead, and the mining operations.

399 —— Mining and milling in the Cœur d'Alene, Idaho.

Eng. & Mg. Jour., vol. 75, p. 87, 1903.

Describes the general geology of the region and the occurrence of ore bodies.

Abstract of a paper read at the New York and Philadelphia meeting of the American Institute of Mining Engineers.

400 **Fippin** (Elmer O.). Soil survey of the Dubuque area, Iowa.
U. S. Dept. Agric., Field Oper. Bur. Soils, 1902, 4th Rept., pp. 571–592, 1903.
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401 —— and **Burgess** (James L.). Soil survey of Howell County, Missouri.
U. S. Dept. Agric., Field Oper. Bur. Soils, 1902, 4th Rept., pp. 593–609, pls. 33–34, 1903.
Includes a brief account of the physiography and geology.

402 —— and **Rice** (Thomas D.). Soil survey of Allegan County, Michigan.
U. S. Dept. Agric., Field Oper. Bur. Soils, 1901, 3d Rept., pp. 93–124, pls. 7–16, 1902.
Includes a brief account of the physiography and geology.

403 **Fletcher** (Hugh). Surveys and explorations in Richmond, Cape Breton, Kings, Cumberland and other counties of Nova Scotia.
Can. Geol. Surv., Summ. Rept. for 1902, pp. 388–399, 1903.
Describes geologic work in the coal fields of Nova Scotia.

404 **Flett** (John S.), **Anderson** (Tempest) and. Preliminary report on the recent eruption of the Soufrière in St. Vincent, and of a visit to Mont Pelée, in Martinique.
See Anderson (Tempest) and Flett (John S.), 32.

405 —— **Anderson** (Tempest) and. Report on the eruptions of the the Soufrière, in St. Vincent, in 1902, and on a visit to Montagne Pelée, in Martinique.
See Anderson (Tempest) and Flett (J. S.), 33.

406 **Fluker** (W. H.). Gold mining in McDuffie County, Georgia.
Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 119–125, 1903.
Describes the occurrence of gold ore and the mining operations.

407 **Foerste** (August F.). The Cincinnati group in western Tennessee, between the Tennessee River and the Central Basin.
Jour. Geol., vol. 11, pp. 29–45, 1 fig., 1903.
Discusses the subdivisions of the Cincinnati group in Ohio, names and describes the subdivisions in Tennessee, and gives localities of outcrops and notes on characteristic fossils.

408 —— Silurian and Devonian limestones of western Tennessee.
Jour. Geol., vol. 11, pp. 554–583, figs. 1–6, pp. 679–715, figs. 7–10, 1903.
Describes character, occurrence and correlation of Silurian strata along the western side of the Cincinnati geanticline in southern Indiana, Kentucky, and northern Tennessee, and of Silurian and Devonian strata in the Tennessee River Valley and discusses evidences for the age of the Cincinnati geanticline and gives lists of fossils with brief descriptions of some forms.

409 **Foerste** (August F.). The Richmond Group along the western side of the Cincinnati anticline in Indiana and Kentucky.

Am. Geol., vol. 31, pp. 333–361, pls. 20–22, 1903.

Discusses occurrence and lithologic, stratigraphic and faunal features of the subdivisions of the Cincinnati series, the decrease in thickness of the Richmond group in Indiana and Kentucky, and conditions prevailing in the region of the Cincinnati anticline in Ordovician times.

410 —— Use of the terms Linden and Clifton limestones in Tennessee geology.

Abstract: Geol. Soc. Am., Bull., vol. 13, p. 531, 1903.

Brief note on the naming of these formations.

411 —— Bearing of Clinton and Osgood formations on age of Cincinnati anticline.

Abstract: Geol. Soc. Am., Bull., vol. 13, pp. 531–532, 1903.

Brief note on the stratigraphic relations of the region.

412 **Fontaine** (Wm. M.). See Diller (J. S.), 302.

413 **Ford** (Frederick L.). The trap rock of the Connecticut Valley.

Stone, vol. 26, pp. 130–133, 1903.

Describes the character, occurrence and geologic history of the trap rock in the vicinity of Hartford, Conn.

414 **Ford** (W. E.). Rickardite, a new mineral.

Am. Jour. Sci., 4th ser., vol. 15, pp. 69–70, 1903; Sci. Am. Suppl., vol. 55, pp. 22777–22778, 1903; Chemical News, vol. 87, pp. 56–57, 1903.

Describes occurence and chemical composition.

415 —— On the chemical composition of axinite.

Am. Jour., Sci., 4th ser., vol. 15, pp. 195–201, 3 figs., 1903.

416 **Foster** (Ernest Le Neve). The Colorado Central lode, a paradox of the mining law.

Colo. Sci. Soc., Proc., vol. 7, pp. 41–53, ill., 1902.

Includes some discussion of the occurrence of the ores.

417 **Frazer** (Persifor). J. Peter Lesley.

Am. Geol., vol. 32, pp. 133–136, pl. 19 (por.), 1903.

418 —— History of the Caribbean Islands from a petrographic point of view. (Abstract).

Phil. Acad. Nat. Sci., Proc., vol. 55, pp. 396–400, 1903.

Discusses briefly the petrology of Cuba and Anglesey and its bearing on the geologic history of the Antillean region.

419 **Frech** (Fritz). Die geographische Verbreitung und Entwickelung des Cambrium.

Cong. Geol. Intern., Compte rendu de la VII Sess., St. Petersburg, pp. 127–151, 1899.

Includes in the discussion the distribution and development of the Cambrian in North America.

420 **Fuller** (Myron L.). Asphalt, oil, and gas in southwestern Indiana.

U. S. Geol. Surv., Bull. no. 213, pp. 333–335, 1903.

Describes occurrence and production of oil, natural gas and asphalt in southwestern Indiana.

421 —— Probable pre-Kansan and Iowan deposits of Long Island, N. Y.

Am. Geol., vol. 32, pp. 308–312, 1903.

422 —— The Horseheads outlet of the Glacial lakes of central New York.

Abstract: Science, new ser., vol. 17, p. 26, 1903.

Discusses Glacial deposits and terraces in this region.

423 —— and **Alden** (William C.). Gaines folio, Pennsylvania-New York.

U. S. Geol. Surv., Geol. Atlas of U. S,, folio no. 92, 1903.

Describes topography and drainage, character and occurrence of Devonian, Carboniferous, and Quaternary deposits, the geologic structure and history, physiography and glacial history, economic products, and discovery and development of the Gaines oil field.

424 —— and **Alden** (William C.). Elkland-Tioga folio, Pennsylvania.

U. S. Geol. Surv., Geol. Atlas of U. S., folio no. 93, 1903.

Describes topography and drainage, character and occurrence of Devonian, Carboniferous, and Quaternary deposits, the geologic structure, geologic, physiographic, and glacial history and economic resources.

425 —— and **Ashley** (George H.). Recent work in the coal field of Indiana and Illinois.

U. S. Geol. Surv., Bull. no. 213, pp. 284–293, 1903.

Describes the character and occurrence of the coals in this area, and thickness and relations of the coal seams.

426 —— and **Clapp** (F. G.). Marl-loess of the lower Wabash Valley.

Geol. Soc. Am., Bull., vol. 14, pp. 153–176, pls. 14–15, 1903; Am. Geol., vol. 31, p. 158, 1903.

Describes character and occurrence of loess deposits in this region and discusses evidences showing their origin.

427 —— and **Veatch** (A. C.). Results of the resurvey of Long Island, New York.

Science, new ser., vol. 18, pp. 729–731, 1903.

Discuss the occurrence of Cretaceous and Quaternary deposits and the source of the water of artesian wells.

428 —— See Campbell (M. R.), 164.

G.

429 **Gallaher** (John A.). Preliminary report on the structural and economic geology of Missouri.

Mo. Bur. Geol. & Mines (Mo. Geol. Surv., vol. 13), Prel. Rept., 251 pp., 63 pls., figs. 1–6, and sections, 1900.

430 **Ganong** (W. F.). Notes on the natural history and physiography of New Brunswick.

New Brunswick Nat. Hist. Soc., Bull., no. 21 (vol. 5, pt. 1), pp. 35–92, ill., 1903.

431 **Gardiner** (J. Stanley). The origin of coral reefs as shown by the Maldives.

Am. Jour. Sci., 4th ser., vol. 16, pp. 203–213, fig. 1, 1903.

432 **Gardner** (Frank D.) and **Stewart** (John). A soil survey in Salt Valley, Utah.

U. S. Dept. Agric., Field Oper. Div. Soils, 1899, pp. 77–114, pls. 10–20, 1900.

Includes an account of physiographic features.

433 —— and **Jensen** (Charles A.). Soil survey in Weber County, Utah.

U. S. Dept. Agric., Field Oper. Div. Soils, 1900, 2d Rept., pp. 207–242, pl. 16, 1901.

Includes an account of physiographic features.

434 —— and **Jensen** (Charles A.). Soil survey in the Sevier Valley, Utah.

U. S. Dept. Agric., Field Oper. Div. Soils, 1900, 2d Rept., pp. 243–285, pls. 17–23, 1901.

Includes an account of physiographic features.

435 —— **Means** (Thomas H.) and. A soil survey in the Pecos Valley, New Mexico.

See Means (T. H.) and Gardner (F. D.), 872.

436 **Gaudry** (Albert). Observations paléontologiques dans l'Alaska.

Acad. des Sci. [Paris], Compt. rend., vol. 137, pp. 553–554, 1903.

Notes the occurrence of Quaternary mammalian remains in Alaska.

437 **Gautier** (Armand). A propos de la composition des gaz des fumerolles du Mont Pelé. Remarques sur l'origine des phénomènes volcaniques.

Acad. des Sci. [Paris], Compt. rend., vol. 136, pp. 16–20, 1903.

Discusses the constitution of gases from the fumaroles of Mont Pelé and the cause of volcanic phenomena.

438 **Gidley** (J. W.). A new three-toed horse.

Am. Mus. Nat. Hist., Bull., vol. 19, pp. 465–476, 1903.

439 —— On two species of Platygonus from the Pliocene of Texas.

Am. Mus. Nat. Hist., Bull., vol. 19, pp. 477–481, figs. 1–5, 1903.

440 —— The fresh-water Tertiary of northwestern Texas. American Museum expeditions of 1899–1901.

Am. Mus. Nat. Hist., Bull., vol. 19, pp. 617–635, pls. 52–58, figs. 1–4, 1903.

Describes explorations in the Tertiary beds of northwestern Texas, and the character, occurence, and fossil contents of Pleistocene, Pliocene, and Miocene formations.

441 **Gilbert** (Grove Karl). John Wesley Powell: a memorial to an American explorer and scholar. Comprising articles by Mrs. M. D. Lincoln (Bessie Beach), Grove Karl Gilbert, Marcus Baker, and Paul Carus. Edited by Grove Karl Gilbert. (Reprinted from "The Open Court.")

Chicago, The Open Court Publishing Company, 75 pp., 4 pls. (por.), 1903.

442 —— Powell as a geologist.

Wash. Acad. Sci., Proc., vol. 5, pp. 113–118, 1903.

443 —— Proposed investigation of subterranean temperatures and gradients.

Carnegie Inst. Wash., Yearbook no. 1, 1902, pp. 285–286, 1903.

Presents a proposition for a deep boring and states results to be obtained thereby.

444 —— John Wesley Powell.

Smith. Inst., Ann. Rept. for 1902, pp. 633–640, por., 1903.

Revised by the author from article published in Science, October 10, 1902. See no. 403 of U. S. Geol. Surv., Bull. no. 221, 1903.

445 —— Joint veins.

Abstract: Geol. Soc. Am., Bull., vol. 13, pp. 521–522, 1903.

Contains brief note on joint structures in the House range, Utah.

446 —— A highly viscous eruption of rhyolite.

Abstract: Science, new ser., vol. 17, p. 221, 1903.

447 —— Physiographic belts in western New York.

Abstract: Science, new ser., vol. 17, p. 221, 1903; Sci. Am. Suppl., p. 22647, 1903.

448 —— Origin of Basin ranges.

Abstract: Science, new ser., vol. 17, p. 301, 1903.

449 —— Statics of a tidal glacier.

Abstract: Science, new ser., vol. 17, pp. 739–740, 1903.

Discusses the statics of tidal glaciers and their bearing upon the origin of fiords.

450 **Gillette** (Halbert Powers). Osmosis as a factor in ore formation.

Am. Inst. Mg. Engrs., Trans. (New York meeting, October, 1903). 5 pp.

451 **Gillot** (H.). Sur la composition chimique des poussières volcaniques de la Martinique.

Soc. Geol. de Belgique, Ann., vol. 30, pp. B49–51, 1903.

Discusses the chemical composition of volcanic ash from Martinique.

452 **Gilmore** (Charles W.). Discovery of dental grooves and teeth in the type of Baptanodon (Sauranodon) Marsh.

Science, new ser., vol. 17, p. 750, 1903.

453 **Giraud** (J.). Sur l'age des formations volcaniques anciennes de la Martinique.

Acad. des Sci. [Paris], Compt. rend., vol. 135, pp. 1377–1379, 1902.

Discusses the geologic age of volcanic formations on the island of Martinique.

454 —— **Lacroix** (A.), **Rollet de l'Isle** and. Sur l'eruption de la Martinique.

See Lacroix (A.), Rollet de l'Isle and Giraud, 727.

455 **Girty** (George H.). The Carboniferous formations and faunas of Colorado.

U. S. Geol. Surv., Professional Paper no. 16, 546 pp., 10 pls., 1903.

Reviews in chronologic order the literature bearing upon the subject and includes a bibliography. Gives a résumé of the literature upon the stratigraphic geology of the Carboniferous area of Colorado. Describes the character and occurrence of the Paleozoic formations, discusses the occurrence and correlation of the Carboniferous fossil faunas by geographic areas and localities, with lists of species, and gives systematic descriptions of the species.

456 —— Tabulated list of invertebrate fossils from the Carboniferous section of Kansas.

U. S. Geol. Surv., Bull. no. 211, pp. 73–83, 1903.

457 —— See Diller, J. S., 302.

458 —— See Washburne (Chester), 1265.

459 **Glenn** (L. C.). Devonic and Carbonic formations of southwestern New York, with stratigraphic map of the Olean quadrangle.

N. Y. State Mus., Bull. 69, pp. 967–989, pls. 1–2, 1903.

Describes occurrence, character, and geologic relations of Devonian and Carboniferous strata of this region and discusses the geologic age of the formations.

460 **Goldschmidt** (Victor) and **Nicol** (William). New forms of sperrylite.

Am. Jour. Sci., 4th ser., vol. 15, pp. 450–458, figs. 1–5, 1903.

Describes crystallographic characters.

461 **Goldthwait** (James Walter), **Huntington** (Ellsworth) and. The hurricane fault in southwestern Utah.

See Huntington (Ellsworth) and Goldthwait (J. W.), 623.

462 **Goode** (John Paul). The piracy of the Yellowstone.

Am. Bur. Geog., Bull., vol. 2, pp. 177–187, ill., 1901.

See no. 2047 in U. S. Geol. Surv., Bull. no. 188.

463 **Gottschalk** (A. L. M.). Gold fields of eastern Nicaragua.

U. S. Dept. Comm. and Labor, Daily Consular Reports, no. 1774, pp. 2–9, 1903.

Describes the occurrence and production of gold.

464 **Grabau** (Amadeus W.). Notes on the development of the biserial arm in certain crinoids

Am. Jour. Sci., 4th ser., vol. 16, pp. 289–300, figs. 1–8, 1903; Columbia Univ., Contr. from Geol. Dept., vol. 11, no. 97, 1903.

465 —— Stratigraphy of Becraft Mountain, Columbia County, N. Y.

N. Y. State Mus., Bull. 69, pp. 1030–1079, figs. 1–13, 1903; Columbia Univ., Contr. from Geol. Dept., vol. 11, no. 98, 1903.

Reviews literature of the region and describes character, occurrence, and fauna of the Ordovician, Silurian, and Devonian strata of Becraft Mountain.

466 —— Paleozoic coral reefs.

Geol. Soc. Am., Bull., vol. 14, pp. 337–352, pls. 47–48, 1903; Columbia Univ., Contr. from Geol. Dept., vol. 11, no. 96, 1903.

Describes coral reefs in the Devonian of Michigan and New York, in the Silurian of Wisconsin and Gotland, and in the Devonian and Carboniferous of Belgium, discusses their formation, and names and describes varieties of reef limestone, and gives a classification of limestones.

467 —— Studies of Gastropoda. II. Fulgur and Sycotypus.

Am. Nat., vol. 37, pp. 515–539, figs. 1–19, 1903; Columbia Univ., Contr. from Geol. Dept., vol. 11, no. 95, 1903.

Describes developmental stages, relationships, and phylogeny of Fulgur and Sycotypus.

468 —— Recent contributions to the problem of Niagara.

Abstract: N. Y. Acad. Sci., Ann., vol. 14, p. 139, 1902.

469 —— Limestone regions of Michigan.

Abstract: N. Y. Acad. Sci., Ann., vol. 15, p. 81, 1903.

470 —— The phylogeny of the Fusidæ.

Abstract: N. Y. Acad. Sci., Ann., vol. 15, pp. 86–87, 1903.

471 —— Traverse group of Michigan.

Abstract: Geol. Soc. Am., Bull., vol. 13, p. 519, 1903.

472 —— **Kemp** (J. F.) and. The Washington meeting of the Geological Society of America, December 30, 31, 1902, January 1 and 2, 1903.

See Kemp (J. F.) and Grabau (A. W.), 676.

473 **Grant** (C. C.). Geological notes.

Hamilton Sci. Assoc., Jour. & Proc., no. 19, pp. 111–127, 5 figs., 1903.

Contains notes on the occurrence of Ordovician and Silurian fossils.

474 —— The origin of petroleum.

Hamilton Sci. Assoc., Jour. & Proc., no. 19, pp. 142–145, 1903.

475 **Grant** (Ulysses Sherman). Preliminary report on the lead and zinc deposits of southwestern Wisconsin.

Wis. Geol. Nat. Hist. Surv., Bull. no. 9, 103 pp., 4 pls., 8 figs., 1903.

Describes topography and general geology of the region and the character, occurrence, and origin of the ore deposits.

476 **Grant** (Ulysses Sherman). Geological excursion in the Pittsburg region.

Geol. Soc. Am., Bull., vol. 14, pp. 3–4, 1903.

Gives a short summary of the stratigraphic, economic, physiographic, and glacial geology of this region.

477 **Graton** (Louis Caryl). On the petrographical relations of the Laurentian limestones and the granite in the township of Glamorgan, Haliburton County, Ontario.

Can. Rec. Sci., vol. 9, pp. 1–38, 1903.

478 —— Up and down the Mississaga [Ontario].

Ont. Bur. Mines [12th] Rept., pp. 157–172, 3 pls., 1903.

Contains observations on the geography, topography, geology, petrography, and resources of the region traversed.

479 **Green** (Raoul). The Frank disaster [Alberta].

Can. Mg. Rev., vol. 22, pp. 103–110, ill., 1903.

Describes the landslide at Frank, Alberta, and discusses its cause.

480 **Greene** (George K.). Contribution to Indiana Paleontology. Part XI.

New Albany, Ind., pp. 98–109, pls. 31–33, 1903.

Includes descriptions of Silurian and Devonian corals and echinoderms, the latter described by Rowley.

481 —— Contribution to Indiana Paleontology. Part XII.

New Albany, Ind., pp. 110–129, pls. 34–36, 1903.

Contains descriptions of Devonian corals and Devonian and Carboniferous echinoderms, the latter by Rowley.

482 —— Contribution to Indiana Paleontology. Part XIII.

New Albany, Ind., pp. 130–136, pls. 37–39, 1903.

Contains descriptions of Devonian corals and echinoderms, the latter by Rowley.

483 —— Contribution to Indiana Paleontology. Part XIV.

New Albany, Ind., pp. 138–145, pls. 40–42, 1903.

Contains descriptions of Devonian corals by Greene and Devonian echinodermata by Rowley.

484 —— Contribution to Indiana Paleontology. Part XV.

New Albany, Ind., pp. 146–155, pls. 43–45, 1903.

Contains descriptions of Devonian corals by Greene and of Devonian echinodermata by Rowley.

485 —— Contribution to Indiana Paleontology. Part XVI.

New Albany, Ind., pp. 156–167, pls. 46–48, 1903.

Contains descriptions of Devonian corals by Greene and of Devonian and Carboniferous echinodermata by Rowley.

486 **Griffith** (William). The anthracite of the Third Hill Mountain, West Virginia; the effect of crushing movements on the quality of the coal.

Mines & Minerals, vol. 23, pp. 293–294, 1 fig., 1903.

Describes the general geology of the region.

487 **Griffiths** (A. B.). The volcanic dust of Mont Pelée.
Chemical News, vol. 88, p. 231, 1903.

488 **Grimsley** (G. P.). Economic geology of Iola [Kansas] and vicinity.
Kans. Acad. Sci., Trans., vol. 18, pp. 78–82, 1 pl., 1903.
Describes production of natural gas and the mineral industries of this locality.

489 **Griswold** (W. T.) Structural work during 1901 and 1902 in the eastern Ohio oil fields.
U. S. Geol. Surv., Bull. no. 213, pp. 336–344, 1903.
Describes factors controlling accumulation of oil, the method used in constructing a map of the oil sand, the structure of the Berea grit, and the development of the field.

490 **Gulliver** (F. P.). Cuttyhunk Island.
Abstract: Geol. Soc. Am., Bull., vol. 13, p. 538, 1903.

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491 **Halberstadt** (Baird). Obituary notice of J. Peter Lesley.
Mines & Minerals, vol. 23, p. 556, por., 1903.

492 **Hale** (David J.). Marl (bog lime) and its application to the manufacture of Portland cement.
Mich. Geol. Surv., vol. 8, pt. 3, pp. 1–399, pls. 1–23, figs. 1–44, 1903.
Describes occurrence and character of marl (bog lime) and discusses the theories of its origin.

493 **Hall** (C. M.), **Todd** (J. E.) and. Alexandria folio, South Dakota.
See Todd (J. E.) and Hall (C. M.), 1211.

494 **Hall** (Christopher Webber). The geography and geology of Minnesota.
Minneapolis, The H. W. Wilson Company. xii, 299 pp., 5 pls., 163 figs., 1903.

495 —— The geology of Minnesota. A description of the various formations in the State, and an account of their products which are of economic value.
Mines & Minerals, vol. 23, pp. 532–534, 1903.
Describes the distribution, lithology, and economic products of the several geologic systems present in the State.

496 **Hallock** (William). An ascent of Mt. Whitney, California, with notes on the geology.
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I.

626 **Iddings** (Joseph Paxson). Chemical composition of igneous rocks expressed by means of diagrams with reference to rock classification on a quantitative chemico-mineralogical basis.

U. S. Geol. Surv., Professional Paper no. 18, 98 pp., 8 pls. (diagrams), 1903.

Reviews the use of diagrams in representing the composition of igneous rocks, discusses the purpose and construction of the diagrams employed by the writer, gives a classified list of analyses used in constructing the diagrams, and a general discussion of igneous rocks as to occurrence, composition, correlation, and classification.

627 —— and others. Quantitative classification of igneous rocks.

See Cross (Whitman) and others, 251.

628 **Ihlseng** (Magnus C.). The road making materials of Pennsylvania.

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638 —— Deposition of ores in limestone.
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Includes a short account of the physiography and geology.

644 —— **Gardner** (Frank D.) and. Soil survey in the Sevier Valley, Utah.
See Gardner (F. D.) and Jensen (C. A.), 434.

645 **Jensen** (Charles A.), **Gardner** (Frank D.) and. Soil survey in Weber County, Utah.

See Gardner (F. D.) and Jensen (C. A.), 433.

646 **Johnson** (Douglas Wilson). Geology of the Cerrillos Hills, New Mexico. Part I. General geology.

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647 —— The geology of the Cerrillos Hills, New Mexico. Part II. Paleontology.

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Am. Geol., vol. 31, pp. 135–139, pl. 12, 1903; Columbia Univ., Contr. from Geol. Dept., vol. 11, no. 93, 1903.

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650 —— Notes on the geology of the saline basins of central New Mexico.

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655 **Jones** (T. Rupert). On some Isochilinæ from Canada and elsewhere in North America.

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657 —— Erosion by flying sand on the beaches of Cape Cod.

Abstract: N. Y. Acad. Sci., Ann., vol. 14, pp. 152–153, 1902.

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658 **Keith** (Arthur). Topography and geology of the southern Appalachians.

Message from the President of the United States, transmitting a report of the Secretary of Agriculture in relation to the forests, rivers, and mountains of the southern Appalachian region (Senate Doc. no. 84, 57th Cong., 1st sess.), pp. 111–123, pls. 58–68, 1902.

Contains a brief account of the general geology of the region.

659 —— Cranberry folio, North Carolina-Tennessee.

U. S. Geol. Surv., Geol. Atlas of U. S., folio no. 90, 1903.

Describes geographic and topographic features, general geologic relations and structure, character and occurrence of Archean, Algonkian, Cambrian, and Juratrias (?) rocks, and mineral resources.

660 —— Iron-ore deposits of the Cranberry district, North Carolina-Tennessee.

U. S. Geol. Surv., Bull. no. 213, pp. 243–246, 1903.

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661 —— Tennessee marbles.

U. S. Geol. Surv., Bull. no. 213, pp. 366–370, 1903.

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662 —— Talc deposits of North Carolina.

U. S. Geol. Surv., Bull. no. 213, pp. 433–438, 1903.

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663 **Kemp** (James Furman). The anthracite situation and problem.

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Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 699–714, 1903.

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667 —— A new spheroidal granite.

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668 —— On the differentiation of igneous magmas and the formation of ores.

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674 —— The leucite hills of Wyoming.

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675 —— Genetic classification of ore deposits.

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676 —— and **Grabau** (A. W.). The Washington meeting of the Geological Society of America, December 30, 31, 1902, January 1 and 2, 1903.

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678 **Kemp** (James Furman), **Finlay** (George I.) and. The nephelite syenite area of San Jose, Tamaulipas, Mexico.
See Finlay (G. I.) and Kemp (J. F.), 397.

679 **Kennedy** (William), **Hayes** (C. W.) and. Oil fields of the Texas-Louisiana Gulf coastal plain.
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680 **Keyes** (Charles Rollin). Geological structure of New Mexican bolson plains.
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682 —— Some recent aspects of the Permian question in America.
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684 —— Geology of the Apache Cañon placers [New Mexico].
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685 —— Significance of the occurrence of minute quantities of metalliferous minerals in rocks.
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694 **Knight** (Nicholas). Apatite crystals, Antwerp, New York.
Am. Geol., vol. 31, p. 62, 1903.

695 **Knight** (Wilbur Clinton). Coal fields of southern Uinta County, Wyoming.
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696 —— Some notes on the genus Baptanodon, with a description of a new species.
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699 **Knowlton** (F. H.). Description of a new fossil species of Chara.
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700 —— See Diller (J. S.), 302.

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707 **Kunz** (George Frederick). On a new lilac-colored transparent spodumene.
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709 —— Native bismuth and bismite from Pala, California.
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713 —— Les enclaves des andésites de l'éruption actuelle de la Montagne Pelée.
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714 —— Nouvelles observations sur les éruptions volcaniques de la Martinique.
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715 **Lacroix** (A.). Sur l'état actuel du volcan de la Montagne Pelée, à la Martinique.

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716 —— État actuel du volcan de la Martinique.

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717 —— Quelques observations minéralogiques faites sur les products de l'incendie de Saint-Pierre (Martinique).

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718 —— Nouvelles observations sur les éruptions volcaniques de la Martinique.

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719 —— Les éruptions des nuages denses de la Montagne Pelée.

Acad. des Sci. [Paris], Compt. rend., vol. 136, pp. 216–218, 1903.

Describes eruptive phenomena of Mont Pelé.

720 —— L'éruption de la Montagne Pelée en janvier, 1903.

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721 —— Sur l'état actuel de la Soufrière de la Guadeloupe.

Acad. des Sci. [Paris], Compt. rend., vol. 136, pp. 656–659, 1903.

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722 —— Sur une éruption du volcan de Saint Vincent.

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723 —— Principaux résultats de la mission de la Martinique.

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724 —— La cordiérite dans les produits éruptifs de la Montagne Pelée et de la Soufrière de Saint Vincent.

Acad. des Sci. [Paris], Compt. rend., vol. 137, pp. 145–147, 1903.

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726 **Lacroix** (A.). Les dernières éruptions de Saint-Vincent.

Ann. de Geog., Paris, no. 63, 12e Année, pp. 261–268, pls. 10–12, 1903.

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728 **Lakes** (Arthur). Aguilar coal and oil district. A description of the geology, the thickness and quality of the coal veins, and the indications of oil.

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729 —— The soils of Colorado in relation to their geological origin and surroundings, and their availability for irrigation.

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730 —— The La Plata Mountains. Observations on their formations and the influence of the different igneous rocks upon mineralization.

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731 —— Recent earth movements. An account of some movements in the Rocky Mountains as shown by effects on streams and mines.

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732 —— Summit County placers of Colorado; a description of the great hydraulic works now nearing completion near Breckenridge.

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Describes the general geology and the occurrence of placer gold.

733 —— Redcliff ore deposits. Not unlike in some respects to the ore deposits of the Mancos contact and the American Nettie at Ouray [Colorado].

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734 —— The Bellevue mining district of Idaho; the geological peculiarities of the veins as shown in the Minnie Moore and the Queen of the Hills mines.

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735 —— Secondary enrichment of ore deposits—its causes and effects—the conclusions of various authorities.

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736 **Lakes** (Arthur). The Silver Lake mine, near Silverton, San Juan County, Colo. An instance of successful operation of a large mine at high altitude.

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Includes notes on the occurrence and geologic relations of the silver-lead ores.

737 —— The present oil situation in Colorado; a review of the histories of the several regions, and the discoveries which have been made.

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Includes an account of the geology of the Boulder oil field.

738 —— Geology and economics along the line of the new Moffat railway, to be built from Denver to Salt Lake City.

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739 —— Creede mining camp. Valuable mines opened through the Nelson and Humphreys tunnels. A description of the Humphreys mill.

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740 —— A trip to Chihuahua, old Mexico. A description of the Descubidoro mine, with some impressions of the country, the people, and the mines.

Mines & Minerals, vol. 23, pp. 446–447, 3 figs., 1903.

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741 —— Zinc deposits: their geology and origin as shown in Wisconsin, Arkansas, Missouri, and Tennessee.

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742 —— Peculiar mines and ore deposits of the Rosita and Silver Cliff mining district of Colorado. Ore deposits in a volcanic throat.

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743 —— Santa Eulalia mines. A trip to the ancient and very rich silver-lead mines in the Santa Eulalia Mountains, near Chihuahua, Mexico.

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744 —— A remarkable occurrence in the depths of a fissure vein.

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745 **Lakes** (Arthur). Geologizing by the seaside. Illustrations of geological phenomena related to mining as shown in the sea cliffs and caves at La Jolla, near San Diego, Cal.

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746 —— The sea and mining. Illustrations shown at seacoast of manner of making and destruction of rocks by action of shellfish and erosion.

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747 —— Mud volcanoes. Present-day illustrations of mudflows and formations resembling some older ones in which mineral deposits have been found.

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748 —— Bonanzas and pockets of ore. Some of the causes of their deposition and origin as illustrated in various mines.

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749 —— Coal and asphalt deposits along the Moffat railway. Geological conditions shown which promise valuable deposits at workable depths.

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Abstract: Science, new ser., vol. 17, pp. 25–26, 1903.

879 —— Chitina copper deposits, Alaska.

Abstract: Science, new ser., vol. 17, p. 387, 1903.

880 **Mendenhall** (Walter C.) and **Schrader** (Frank C.). The mineral resources of the Mount Wrangell district, Alaska.

U. S. Geol. Surv., Professional Paper no. 15, 71 pp., 10 pls., 5 figs., 1903.

Gives a résumé of the previous explorations in this region, and describes the general geology and physiography and occurrences of copper, gold, and other minerals of the region.

881 —— and **Schrader** (Frank C.). Copper deposits of the Mount Wrangell region, Alaska.

U. S. Geol. Surv., Bull. no. 213, pp. 141–148, 1903.

Gives a brief account of the geology and occurrences of copper-bearing ores in this region and the mining developments.

882 **Merriam** (John C.). New Ichthyosauria from the upper Triassic of California.

Cal. Univ., Dept. Geol., Bull., vol. 3, pp. 249–263, pls. 21–24, 1903.

883 —— The Pliocene and Quaternary Canidæ of the Great Valley of California.

Cal. Univ., Dept. Geol., Bull., vol. 3, pp. 277–290, pls. 28–30, 1903.

884 —— Recent literature on Triassic Ichthyosauria.

Science, new ser., vol. 18, pp. 311–312, 1903.

885 —— Primitive characters of the Triassic Ichthyosaurus.

Abstract: Science, new ser., vol. 17, p. 297, 1903.

886 —— and **Sinclair** (William J.). The correlation of the John Day and the Mascall.

Abstract: Jour. Geol., vol. 11, pp. 95–96, 1903.

Discusses the age of the beds from a study of the fauna.

887 **Merrill** (Frederick J. H.). Report of the director of the State Museum and State geologist for the year 1901.

N. Y. State Mus., 55th Ann. Rept., pp. r5–r166, 1903.

Reviews the administrative and scientific work of the year.

888 **Merrill** (George Perkins). A newly found meteorite from Mount Vernon, Christian County, Kentucky.

Am. Geol., vol. 31, pp. 156–158, 1903.

889 —— John Wesley Powell.

Am. Geol., vol. 31, pp. 327–333, pl. 19 (por.), 1903.

890 —— The quantitative classification of igneous rocks.

Am. Geol., vol. 32, pp. 48–54, 1903.

Gives an outline of the nomenclature and classification used in the "Quantitative Classification of Igneous Rocks" of Cross, Iddings, Pirsson, and Washington, see no. 251. Includes a table by E. B. Mathews showing the new nomenclature and terminology as applied to some of the better known igneous rocks.

891 **Merrill** (George Perkins). On the Glacial pothole in the National Museum.

Smith. Misc. Coll., vol. 45, pp. 100–103, pl. 31, 1903.

Describes a pothole brought from Maine and the method employed in removing it from its matrix.

892 —— Stones for building and decoration. Third edition.

New York, John Wiley & Sons, xi, 551 pp., 33 pls., 24 figs., 1903.

893 **Mesmer** (Louis). Soil survey of the Lewiston area, Idaho.

U. S. Dept. Agric., Field Oper. Bur. Soils, 1902, 4th Rept., pp. 689–709, 1903.

Includes an account of the physiography and geology.

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U. S. Dept. Agric., Field Oper. Bur. Soils, 1902, 4th Rept., pp. 125–142, pls. 1–2, 1903.

Includes a short account of the physiography and geology.

895 —— and **Caine** (Thomas A.), **Dorsey** (Clarence W.) Soil survey from Arecibo to Ponce, Porto Rico.

See Dorsey (C. W.), Mesmer (Louis), and Caine (T. A.), 315.

896 —— **Heileman** (W. H.) and. Soil survey of the Lake Charles area, Louisiana.

See Heileman (W. H.) and Mesmer (Louis), 541.

897 —— **Holmes** (J. Garnett) and. Soil survey of the Ventura area, California.

See Holmes (J. G.) and Mesmer (Louis), 599.

898 **Meunier** (Stanislaus). Remarque sur l'origine de l'activité volcanique.

Acad. des Sci. [Paris] Compt. rend., vol. 136, pp. 123–124, 1903.

Discusses the cause of volcanic phenomena.

899 **Miers** (Henry A.). Gold mining in Klondike.

Roy. Inst. Gt. Brit., Proc., vol. 17, pp. 72–81, 1903.

Describes physiographic features, general geology, occurrence of placer gold, mining operations, and prospects in the Klondike region.

900 **Miller** (Arthur M.) A new meteorite (Bath Furnace) from Kentucky.

Abstract: Eng. & Mg. Jour., vol. 75, p. 154, 1903; Science, new ser., vol. 17, p. 228, 1903; Sci. Am. Suppl., vol. 55, p. 22666, 1903.

901 —— Additional facts concerning the Bath Furnace meteoric fall of November 15, 1902.

Science, new ser., vol. 18, pp. 243–244, 1903.

902 **Miller** (Elmer I.). A week in the Mt. Lassen and cinder cone region of northern California.

Am. Bur. Geog., Bull., vol. 2, pp. 150–156, 1901.

Describes physiographic features of this region and discusses the evidences for determining the time of the volcanic activity of Mount Lassen.

903 **Miller** (G. W.). The Verde mining district, Yavapai County, Arizona.

Mg. & Sci. Press, vol, 86, pp. 70–71, 3 figs., 1903.

Gives an account of the geology of the district and the occurrence of the copper ore deposits.

904 **Miller** (M. F.), **Lapham** (J. E.) and. Soil survey of Montgomery County, Tennessee.

See Lapham (J. E.) and Miller (M. F.), 769.

905 **Miller** (Willet G.). Nepheline syenite in western Ontario.

Am. Geol., vol. 32, pp. 182–185, 1903.

Describes occurrence and composition.

906 —— Cobalt-nickel arsenides and silver in Ontario.

Eng. & Mg. Jour., vol. 76, pp. 888–890, 1903.

Describes the occurrence and character of these ore bodies.

907 —— Iron ranges of northern Ontario.

Ont. Bur. Mines, [12th] Rept., pp. 304–317, 4 figs., 1903.

Describes occurrences of iron ores.

908 —— [In discussion of paper by Waldemar Lindgren, "The geological features of the gold production of North America."]

Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 1077–1079, 1903.

Discusses occurrences of gold in Canada and conditions under which they can be worked.

909 **Mills** (Frank S.). River terraces and reversed drainage [New York].

Jour. Geol., vol. 11, pp. 670–678, figs. 1–3, 1903.

Describes physiographic features in the Catatonk River Valley in southern New York and their bearing upon pre-Glacial drainage conditions.

910 —— The delta-plain at Andover, Mass.

Am. Geol., vol. 32, pp. 162–170, pls. 22–24, 1903.

Describes glacial and physiographic features of this locality.

911 **Milne** (J.). West Indian volcanic eruptions.

Nature, vol. 67, pp. 91–92, 1902.

Discusses volcanic phenomena and their causes with especial reference to the volcanoes Pelé and St. Vincent.

912 **Moffet** (Fred H.). The copper mines of Cobre, Santiago de Cuba.

Abstract: Am. Geol., vol. 32, p. 64, 1903; Science, new ser., vol. 18, p. 18, 1903.

913 **Moissan** (Henri). Sur la présence de l'argon, de l'oxyde de carbone et des carbures d'hydrogène dans les gaz des fumerolles du Mont Pelé à la Martinique.

Acad. des Sci. [Paris], Compt. rend., vol. 135, pp. 1085–1088, 1902.

Describes investigations upon the constitution of gases collected from a fumarole of Mont Pelé.

914 **Montessus de Ballore** (D. de). Les États-Unis sismiques.

Arch. des Sci. Phys. et Nat., 4th ser., vol. 5, pp. 201–216, pl. 3, 1898.

Gives notes upon and lists of earthquakes that have occurred in various parts of the United States.

915 **Mooney** (Charles N.), **Martin** (J. O.), and **Caine** (Thomas A.). Soil survey of the Bedford area, Virginia.

U. S. Dept. Agric., Field Oper. Bur. Soils, 1901, 3d Rept., pp. 239–257, pls. 26–31, 1902.

Includes a brief account of the physiography and geology.

916 —— and **Caine** (Thomas A.). Soil survey of the Prince Edward area, Virginia.

U. S. Dept. Agric., Field Oper. Bur. Soils, 1901, 3d Rept., pp. 259–271, 1902.

Includes a brief account of the physiography and geology.

917 —— and **Bonsteel** (F. E.). Soil survey of the Albemarle area, Virginia.

U. S. Dept. Agric., Field Oper. Bur. Soils, 1902, 4th Rept., pp. 187–238, pls. 5–7, 1903.

Includes a brief account of the physiography and geology.

918 **Morris** (Henry G.). Hydro-thermal activity in the veins at Wedekind, Nevada.

Eng. & Mg. Jour., vol. 76, pp. 275–276, ill., 1903.

Discusses the geologic structure and the origin of the ores.

919 **Moses** (Alfred J.). Eglestonite, terlinguaite, and montroydite, new mercury minerals from Terlingua, Texas.

Am. Jour. Sci., 4th ser., vol. 16, pp. 253–263, figs. 1–6, 1903.

Describes crystallographic and other characters and composition.

920 —— and **Luquer** (Lea McI.). Notes on recent mineralogical literature.

School of Mines Quart., vol. 24, pp. 247–266, 1903.

921 **Moudy** (R. B.), **Slosson** (E. E.) and. The Laramie cement plaster.

See Slosson (E. E.) and Moudy (R. B.), 1120.

922 **Mügge** (O.). Ueber die Structur des grönländischen Inlandeises und ihre Bedeutung für die Theorie der Gletscherbewegung.

Neues Jahrb. f. Min., Jahrg. 1899, bd. 2, pp. 123–136, 1899.

Discusses the structure and movement of ice in the interior of Greenland and its bearing upon the theory of the movement of glaciers.

923 —— Weitere Versuche über die Translationsfähigkeit des Eises, nebst Bemerkungen über die Bedeutung der Structure des grönländischen Inlandeises.

Neues Jahrb. f. Min., Jahrg. 1900, bd. 2, pp. 80–98, 1900.

Discusses the plasticity of ice, and the significance of the structure of the ice-mass in Greenland.

924 **Myers** (E. W.), **Pressey** (H. A.) and. Hydrography of the southern Appalachians.

See Pressey (H. A.) and Myers (E. W.), 977.

N.

925 **Neill** (N. P.), **Jensen** (Charles A.) and. Soil survey of the Billings area, Montana.

See Jensen (C. A.) and Neill (N. P.), 642.

926 —— **Jensen** (Charles A.) and. Soil survey of the Grand Forks area, North Dakota.

See Jensen (C. A.) and Neill (N. P.), 643.

927 **Nelson** (Aven). Wilbur Clinton Knight.

Science, new ser., vol. 18, pp. 406–409, 1903.

Gives a short account of his life and work, and a chronologic list of his papers.

928 **Nevius** (J. Nelson). The Sain Alto tin deposits [Mexico].

Eng. & Mg. Jour., vol. 75, p. 929, 1903.

Describes the occurrence of tin.

929 **Newsom** (John Flesher). A geologic and topographic section across southern Indiana from the Ohio River at Hanover to the Wabash River at Vincennes, with a discussion of the general distribution and character of the Knobstone group in the State of Indiana.

Ind. Dept. Geol. & Nat. Res., 26th Ann. Rept., pp. 227–302, pls. 1–7, figs. 1–19, 1903.

Describes topographic and drainage features, the stratigraphy, character, and geological relations of formations of Ordovician, Silurian, Devonian, and Carboniferous age, and discusses the geologic history of the region.

930 —— Clastic dikes.

Geol. Soc. Am., Bull., vol. 14, pp. 227–268, pls. 21–31, figs. 1–19, 1903.

Describes location, geologic relations, character, and origin of clastic dikes, chiefly those of California, and gives references to literature in which clastic dikes are described.

931 **Nicholson** (Frank). The Wisconsin zinc-fields.

Eng. & Mg. Jour., vol. 76, pp. 847–849, ill., 1903.

Describes the general geology of the region and the occurrence and character of the zinc and lead ore deposits and the mining operations.

932 **Nickles** (John M.). The Richmond group in Ohio and Indiana and its subdivisions, with a note on the genus Strophomena and its type.

Am. Geol., vol. 32, pp. 202–218, 1903.

933 **Nicol** (William), **Goldschmidt** (Victor) and. New forms of sperrylite.

See Goldschmidt (Victor) and Nicol (William), 460.

934 **Nolan** (A. W.) and **Dixon** (J. D.). Geology of St. Helen's Island [Quebec].

Can. Rec. Sci., vol. 9, pp. 53–66, figs. 1–5, 1903.

Discusses the character and occurrence of Ordovician and Devonian strata, the character, occurrence, and origin of the breccia formation of the island, and the petrography of the intersecting dikes.

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935 **O'Brien** (Charles J.). Igneous rocks: How to identify them.

Mg. & Sci. Press, vol. 87, p. 50, 1903.

936 **O'Brien** (M. E.). Geology of the district west of Redding, Cal.

Mg. & Sci. Press, vol. 86, p. 349, 1903.

Describes the character and occurrence of the rock formations and ore deposits.

937 **Olshausen** (B. A.), **Lapham** (J. E.) and. Soil survey of the Wichita area, Kansas.

See Lapham (J. E.) and Olshausen (B. A.), 770.

938 —— **Jensen** (Charles A.) and. Soil survey of the Boise area, Idaho.

See Jensen (C. A.) and Olshausen (B. A.), 641.

939 —— **Jensen** (Charles A.) and. Soil survey of the Yakima area, Washington.

See Jensen (Charles A.) and Olshausen (B. A.), 640.

940 **Olsson-Seffer** (Pehr). Examination of organic remains in post-Glacial deposits.

Am. Nat., vol. 37, pp. 785–797, figs. 1–2, 1903.

Discusses methods of collecting and examining plant remains from Quaternary deposits, particularly from peat-bogs.

941 **Ordoñez** (Ezequiel). Le Xinantacatl ou volcan Nevado de Toluca [Mexico].

Soc. Cient. Ant. Alz., Mem. y Rev., vol. 18, pp. 83–112, pls. 5–9, 1902.

Describes physiographic features, the character and occurrence of igneous rocks, and the history of its volcanic activity, and compares its physical features with those of other Mexican volcanoes.

942 —— El Sahcab de Yucatan.

Soc. Cient. Ant. Alz., Mem. y Rev., vol. 18, pp. 217–223, 1902.

Describes the character and occurrence of some geologic formations in this part of Mexico.

943 —— Los volcanes de Zacapu, Michoacan [Mexico].

Soc. Cient. Ant. Alz., vol. 18, pp. 257–265, pl. 14, 1902.

Describes physiographic features of the volcanoes of this region and the character and occurrence of igneous rocks.

944 —— Les dernières éruptions du volcan de Colima [Mexico].

Soc. Cien. Ant. Alz., Mem. y Rev., vol. 20, pp. 99–104, pls. 3–4, 1903.

Describes eruption phenomena and eruptive products of this volcano.

944a **Orton** (Edward, jr.). The organization and work of the Geological Survey of Ohio.

Ohio Geol. Surv., 4th ser., Bull. no. 1, pp. i–xxi, 1903.

Gives an outline of the work and publications of the preceding and present organizations of the geological survey of Ohio.

945 **Osborn** (Henry Fairfield). Ornitholestes hermanni, a new compsognathoid dinosaur from the upper Jurassic.

Am. Mus. Nat. Hist., Bull., vol. 19, pp. 459–464, figs. 1–3, 1903.

946 —— Glyptotherium texanum, a new glyptodont, from the lower Pleistocene of Texas.

Am. Mus. Nat. Hist., Bull., vol. 19, pp. 491–494, pl. 43, 1903.

947 —— The skull of Creosaurus.

Am. Mus. Nat. Hist., Bull., vol. 19, pp. 697–701, figs. 1–2, 1903.

948 —— The reptilian subclasses Diapsida and Synapsida and the early history of the Diaptosauria.

Am. Mus. Nat. Hist., Mem., vol. 1, pt. 8, pp. 451–507, pl. 40, figs. 1–24, 1903.

Discusses classification, anatomy, and phylogeny of fossil reptiles and defines the major classification groups and genera.

949 —— Recent zoopaleontology.

Science, new ser., vol. 17, pp. 312–314, 1903.

Includes a brief discussion of the age of the Fort Union beds and related formations.

950 —— Recent zoopaleontology.

Science, new ser., vol. 17, pp. 356–357, 1903.

Discusses the age of the typical Judith River beds.

951 —— Recent zoopaleontology.

Science, new ser., vol. 17, pp. 673–674, 1903.

Gives a comparison of the European and American Eocene horses.

952 —— Evolution of the Proboscidea in North America.

Abstract: Science, new ser., vol. 17, p. 249, 1903.

953 —— On recent models and restorations of a number of extinct animals, with a discussion of their probable habits and mode of life.

Abstract: Science, new ser., vol. 17, p. 978, 1903.

954 —— Vertebrate paleontology in the United States Geological Survey.

Science, new ser., vol. 18, pp. 835–837, 1903.

Describes the work being done to complete Professor Marsh's monographs on the Titanotheres, Ceratopsia, Stegosauria, and Sauropoda.

955 **Owen** (Luella A.). More concerning the Lansing skeleton.

Bibliotheca Sacra, 73d yr., pp. 572–578, 1903.

Reviews the discussion as to the geological age of the Lansing skeleton.

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956 **Palmer** (Charles M.). Chrysocolla: a remarkable case of hydration.

Am. Jour. Sci., 4th ser., vol. 16, pp. 45–48, 1903.

Gives composition and describes absorption of water.

957 **Parks** (William Arthur). Region lying northeast of Nipigon Lake.

Can. Geol. Surv., Summ. Rept. for 1902, pp. 211–220, 1903.

Gives observations upon the physiography, geology, and economic resources of the region examined.

958 —— Fossiliferous rocks of southwest Ontario.

Ont. Bur. Mines [12th] Rept., pp. 141–156, 1903.

Describes location, lithologic and stratigraphic features of outcrops of Silurian and Devonian strata of southwest Ontario, and gives lists of fossils obtained and discusses economic resources.

959 **Parsons** (H. F.) and **Liddell** (Charles A.). The coal and mineral resources of Routt County [Colorado].

Colo. Sch. Mines, Bull., vol. 1, no. 4, pp. 47–59, ill., 1903.

Describes the geology, the location of the coal districts, the character and occurrence of the Cretaceous coals, and the occurrence of other mineral deposits, chiefly gold.

960 **Patton** (Horace B.). Synopsis of paper on the development of pseudomorphs.

Colo. Sci. Soc., Proc., vol. 7, pp. 103–107, figs. 1–7, 1903.

Discusses the methods of alteration of minerals and describes dolomite and calcite crystals from Colorado.

961 **Peale** (A. C.). The classification of mineral waters with especial reference to the characteristics and geographic distribution of the medicinal springs of the United States.

Cohen's System of Physiologic Therapeutics, vol. 9, pp. 299–365, 1902.

962 **Pearce** (Richard). Notes on the occurrence of selenium with pyrite rich in gold and silver [from Mexico], and remarks on a gold nugget from Montana.

Colo. Sci. Soc., Proc., vol. 6, pp. 157–159 [1902].

963 **Pearson** (Karl). The fossil man of Lansing, Kansas.

Nature, vol. 68, p. 7, 1903.

Discusses in the light of measurements of the bones the height of the individual.

964 **Peck** (Frederick B.). The basal conglomerate in Lehigh and Northampton counties, Pennsylvania.

Abstract: Science, new ser., vol. 17, p. 291, 1903; Eng. & Mg. Jour., vol. 75, p. 154, 1903.

Describes its occurrence and characters.

965 **Penfield** (S. L.). Tables of minerals, including the uses of minerals and statistics of the domestic production.

New Haven, Conn., 77 pp., 1903.

966 **Penhallow** (D. P.). Osmundites skidegatensis n. sp.

Can. Roy. Soc., Proc. & Trans., 2d ser., vol. 8, sect. 4, pp. 3–30, pls. 1–6, figs. 1–3, 1902.

Describes megascopic characters and microscopic structure of this fossil plant.

967 —— Notes on Cretaceous and Tertiary plants of Canada.

Can. Roy. Soc., Proc. & Trans., 2d ser., vol. 8, sect. 4, pp. 31–92, pls. 7–16, figs. 1–8, 1902.

968 —— Notes on Tertiary plants.

Can. Roy. Soc., Trans., 2d ser., vol. 9, sect. 4, pp. 33–71, 29 figs., 1903.

Gives descriptions of plants, especially of internal structure as revealed by microscopic sections, of early Tertiary age, based upon material obtained by the British North American Boundary Commission.

969 **Penrose** (R. A. F., jr.). Present condition of gold mining in Arctic America.

Eng. & Mg. Jour., vol. 76, pp. 807–809, 852–853, ill., 1903.

970 **Perry** (Joseph H.). Notes on the geology of Mount Kearsarge, New Hampshire.

Jour. Geol., vol. 11, pp. 403–412, figs. 1–2, 1903.

Describes the petrologic characters of the rocks composing this mountain.

971 —— and **Emerson** (Benjamin K.). The geology of Worcester, Massachusetts.

Worcester Nat. Hist. Soc., 166 pp., ill., 1903.

Describes character, occurrence and relations of rocks of Worcester and gives an account of the general geology of the surrounding region.

972 **Pirsson** (Louis V.) and others. Quantitative classification of igneous rocks.

See Cross (Whitman) and others, 251.

973 **Poole** (Henry S.). Notes on Dr. Ami's paper on Dictyonema slates of Angus Brook, New Canaan, and Kentville, N. S.

Nova Scotian Inst. Sci., Proc. & Trans., vol. 10, pp. 451–454, 1903.

974 —— Notes on the geology of Anthracite, Alberta.

Can. Geol. Surv., Summ. Rept. for 1902, pp. 147–149, 1903.

Describes geologic features developed by the coal mining operations.

975 —— The Carboniferous rocks of Chignecto Bay.

Can. Geol. Surv., Summ. Rept. for 1902, pp. 377–382, 1903.

Describes results of geologic examination of the Carboniferous area of this region.

976 —— A submerged tributary to the great pre-Glacial river of the Gulf of St. Lawrence.

Can. Roy. Soc., Proc. & Trans., 2d ser., vol. 9, sect. 4, pp. 143–147, 1 fig., 1903.

977 **Pressey** (H. A.) and **Myers** (E. W.). Hydrography of the southern Appalachians.

Message from the President of the United States, transmitting a report of the Secretary of Agriculture in relation to the forests, rivers, and mountains of the southern Appalachian region (Senate Doc. no. 84, 57th Cong., 1st sess.), pp. 123–142, pls. 69–78, 1902.

Describes physiographic features of the region.

978 **Prest** (Walter H.). Supplementary notes on drift ice as a transporting agent.

Nova Scotian Inst. Sci., Proc. & Trans., vol. 10, pp. 455–457, 1903.

979 **Preston** (H. L.). Reed City [Michigan] meteorite.

Jour. Geol., vol. 11, pp. 230–233, figs. 1–2, 1903; Rochester Acad. Sci., Proc., vol. 4, pp. 89–91, pl. 12, 1903.

980 **Prichard** (W. R.). Observations on Mother Lode gold deposits, California.

Eng. & Mg. Jour., vol. 76, pp. 125–127, 1903; Am. Inst. Mg. Engrs., Trans. (New York meeting, October, 1903), 13 pp.

Describes the geologic structure and occurrence of the ore deposits.

981 **Probert** (Frank H.). Secondary enrichment.

Eng. & Mg. Jour., vol. 76, pp. 958–959, figs. 1–5, 1903.

Describes the general geology and the origin of the copper-ore deposits of the Clifton-Morenci district in Arizona.

982 **Prosser** (Charles S.). The nomenclature of the Ohio geological formations.

Jour. Geol., vol. 11, pp. 519–546, 1903; Ohio State Univ. Bull., ser. 8, no. 3 (Geol. ser., no. 6), 1903.

Gives a table of the formations of the geological scale in Ohio and discusses their nomenclature and correlations.

983 —— Notes on the geology of eastern New York.

Am. Geol., vol. 32, pp. 381–384, 1903.

Discusses relations and nomenclature of Silurian and Devonian formations in eastern New York.

984 **Purdue** (A. H.). The saddle-back topography of the Boone chert region, Arkansas.

Abstract: Science, new ser., vol. 17, p. 222, 1903; Sci. Am. Suppl., vol. 55, p. 22666, 1903.

985 **Purington** (Chester Wells). The Contact, Nevada, quaquaversal.

Colo. Sci. Soc., Proc., vol. 7, pp. 127–138, figs. 1–5, 1903.

Describes physiographic features and the geologic structure of the region and the occurrence of ore bodies.

986 —— The Camp Bird mine, Ouray, Colorado, and the mining and milling of the ore.

Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 499–528, figs. 1–10, 1903.

Describes the general geology of the region, the system of veins and fissures, the occurrence of the ores, principally galena, and discusses the origin of the ore deposits.

987 **Purington** (Chester Wells). Secondary enrichment.

Eng. & Mg. Jour., vol. 75, pp. 472–473, 1903.

988 —— The geological structure of the Camp Bird vein [Colorado].

Eng. & Mg. Jour., vol. 75, pp. 820–822, figs. 1–2, 1903.

Describes the veins and fissures and their rock contents, and the character and occurrence of the gold and silver ores.

989 —— Observations on gold deposits.

Eng. & Mg. Jour., vol. 75, pp. 854–855, 893–894, 929–931, 1903.

Discusses occurrence and origin of gold deposits in various regions of the world.

990 —— Geology of the Virginius mine [Colorado].

Eng. & Mg. Jour., vol. 76, p. 458, 1903.

Discusses the occurrence and origin of the gold ores.

R.

991 **Ransome** (Frederick Leslie). Geology of the Globe copper district, Arizona.

U. S. Geol. Surv., Professional Paper no. 12, 168 pp., pls. 1–27, figs. 1–10, 1903.

Gives an outline of the physiography of Arizona and topography and general geology of the Globe quadrangle, and describes the character and occurrence of igneous rocks and sedimentary strata of Cambrian, Devonian, Carboniferous, Eocene (?), and Quaternary age, the character, occurrence, and origin of the ores, chiefly gold, silver, and copper, and the mining operations.

992 —— Copper deposits of Bisbee, Ariz.

U. S. Geol. Surv., Bull. no. 213, pp. 149–157, 1903.

Describes the general geology of the region, the occurrence and origin of the ores, and the mining operations.

993 —— The copper deposits of Bisbee, Arizona.

Eng. & Mg. Jour., vol. 75, pp. 444–445, 2 figs., 1903.

Describes the geologic structure of the region and the character and occurrence of the ore deposits.

994 —— The geology and copper deposits of Bisbee, Arizona.

Am. Inst. Mg. Engrs., Trans. (Albany meeting, February, 1903), 26 pp.

Describes the geography and general geology, the character, occurrence, and relations of the Paleozoic and Mesozoic sedimentary strata, the intrusions and deformation, the character, occurrence, and origin of the copper-ore deposits, and the mining operations.

995 —— Genetic classification of ore deposits.

Abstract: Science, new ser., vol. 17, p. 542, 1903.

996 **Ravn** (J. P. J.). The Tertiary fauna at Kap Dalton in East Greenland.

Meddelelser om Groenland, vol. 29, pp. 93–140, pls. 3–5, 1903: Copenhagen Univ., Mus. Min. et Geol., Comm., Paléont., no. 4, 1903.

Reviews discoveries of fossils in Greenland and the geologic age of the formations from which they were obtained, describes a fauna, mainly molluscan, obtained from East Greenland and discusses its geologic horizon.

997 **Raymond** (Percy E.). The faunas of the Trenton at the type section and at Newport, N. Y.

Am. Pal., Bull., no. 17, pp. 13–26, 1903.

Discusses the occurrence and range of faunules in Trenton sections.

998 **Raymond** (R. W.). Biographical notice of Clarence King.

Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 619–650, por., 1903.

999 **Raymond** (William J.). Writings of James G. Cooper, M. D., on conchology and paleontology, with list of species described by him.

Nautilus, vol. 17, pp. 6–12, 1903.

1000 **Read** (Thomas T.). Preliminary note upon the rare metals in the ore from the Rambler mine, Wyoming.

Am. Jour. Sci., 4th ser., vol. 16, p. 268, 1903.

1001 —— Nodular-bearing schists near Pearl, Colorado.

Jour. Geol., vol. 11, pp. 493–497, figs. 1–2, 1903.

Gives observations on the petrology of the area.

1002 **Reade** (T. Mellard). The evolution of earth structure, with a theory of geomorphic changes.

London, Longmans, Green & Co., xv, 342 pp., 40 pls., 1903.

Includes papers by the author on "Denudation of the two Americas" and "The north atlantic as a geological basin," reprinted from the Proceedings of the Liverpool Geological Society, vol. 5, pts. 1 and 2, 1885 and 1886.

1003 **Reagan** (Albert B.). Geology of the Jemez-Albuquerque region, New Mexico.

Am. Geol., vol. 31, pp. 67–111, pls. 4–10, 1903.

Describes general geologic relations and structure, character, and occurrence of strata of Carboniferous, Mesozoic, Tertiary, and Quaternary age, geographic and physiographic features, and economic resources of this region.

1004 —— Age of the lavas of the plateau region [New Mexico and Arizona].

Am. Geol., vol. 32, pp. 170–177, 1903.

Gives stratigraphic sections of strata of Permo-Carboniferous, Tertiary, and Quaternary age of this region and discusses age of included lava sheets.

1005 —— Geology of the Fort Apache region in Arizona.

Am. Geol., vol. 32, pp. 265–308, pls. 29–30, 1 fig., 1903.

Describes geography, physiography, drainage, and general geological structure, occurrence and character of strata of Archean, Algonkian, Silurian, Devonian, Tertiary, and Quaternary age, and intrusive rocks, and discusses origin of Quaternary and Tertiary deposits, and the economic resources of the region.

1006 —— The Jemez coal fields [New Mexico].

Ind. Acad. Sci. Proc., 1902, pp. 197–198, 1903.

Gives a short account of the geology and the occurrence and character of the coal strata.

1007 **Redway** (Jacques W.). A great lava flood.
Am. Bur. Geog., Bull., vol. 2, pp. 157–163, figs. 1–3, 1901.
Defines types of volcanic outflows and describes the Tertiary lava flows of the Pacific region.

1008 **Reid** (Harry Fielding). [The variation of glaciers in North America.]
Arch. d. Sci. phys. et nat., vol. 14, pp. 301–302, 1902.

1009 —— The variation of glaciers VIII.
Jour. Geol., vol. 11, pp. 285–288, 1903.
Gives a summary of the seventh annual report of the International Committee on Glaciers and reports on the glaciers of the United States for 1902.

1010 —— Glaciers.
Mazama, vol. 2, no. 3, pp. 119–122, 1903.
Describes formation and phenomena of glaciers.

1011 —— Notes on Mounts Hood and Adams and their glaciers.
Abstract: Geol. Soc. Am. Bull., vol. 13, p. 536, 1903.

1012 **Rice** (Thomas D.) and **Taylor** (F. W.). Soil survey of the Darlington area, South Carolina.
U. S. Dept. Agric., Field Oper. Bur. Soils, 1902, 4th Rept., pp. 291–307, pls. 12–15, 1903.
Includes a short account of the physiography and geology.

1013 —— **Fippin** (Elmer O.) and. Soil survey of Allegan County, Michigan.
See Fippin (E. O.) and Rice (T. D.), 402.

1014 —— **Taylor** (F. W.) and. Soil survey of the Abbeville area, South Carolina.
See Taylor (F. W.) and Rice (T. D.), 1198.

1015 **Richardson** (George Burr). The upper Red Beds of the Black Hills.
Jour. Geol., vol. 11, pp. 365–393, 4 figs., 1903.
Describes physical characters, geographic extent, general geological relations, and stratigraphy of the Red Beds in the Black Hills, and discusses the orgin of their color.

1016 **Rickard** (Edgar). Tin deposits of the York region, Alaska.
Eng. & Mg. Jour., vol. 75, pp. 30–31, 1903.
Describes the geology of the region and the occurrence of tin.

1017 **Rickard** (T. A.). Across the San Juan Mountains.
New York, The Engineering and Mining Journal, 115 pp., ill., 1903; appeared serially in the Eng. & Mg. Jour., vol. 76, pp. 7–10, 45–46, 82–84, 118–119, 154–155, 230, 269–270, 307–308, 346, 385–387, 423–424, 461–463, ill., 1903.
Contains observations on the geologic structure, ore deposits, and mining operations of southwestern Colorado.

1018 **Rickard** (T. A.). The lodes of Cripple Creek [Colorado].

Eng. & Mg. Jour., vol. 75, pp. 179–181, figs. 1–5, 1903.

Discusses the occurrence of ore bodies.

1019 —— Water in veins—a theory.

Eng. & Mg. Jour., vol. 75, pp. 402–403, 1903.

Discusses the distribution of water under ground and its bearing upon the origin of ore deposits.

1020 —— The syncline as a structural type.

Eng. & Mg. Jour., vol. 75, p. 746, figs. 1–6, 1903.

Discusses the syncline in relation to ore deposits.

1021 —— The veins of Boulder and Kalgoorlie.

Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 567–577, figs. 1–5, 1903.

Describes the occurrence, character, and structure of gold-bearing veins of Boulder, Colorado, and Kalgoorlie, West Australia.

1022 —— The lodes of Cripple Creek [Colorado].

Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 578–618, figs. 1–23, 1903.

Describes the general geology of the region, the occurrence and character of the lodes and veins, and the position of the ore bodies.

1023 —— Genetic classification of ore deposits.

Abstract: Science, new ser., vol. 17, p. 542, 1903.

1024 **Ries** (Heinrich). The clays of the United States east of the Mississippi River.

U. S. Geol. Surv., Professional Paper no. 11, 298 pp., 9 pls., 11 figs., 1903.

Discusses origin, geographic and geologic distribution of clays in the United States east of the Mississippi River, and their properties, composition, and utilization.

1025 —— Uses of peat and its occurrence in New York.

N. Y. State Mus., 55th Ann. Rept., pp. r53–r90, pls. 32–36, 1903.

Describes origin and nature of peat, its utilization, and its occurrence in the State of New York.

1026 —— Magnetite deposits at Mineville, New York, and a description of the new electric concentrating plant.

Mines & Minerals, vol. 24, pp. 49–51, figs. 1–5, 1903.

Describes the character and occurrence of the iron ore deposits.

1027 —— The coal mines at Las Esperanzas, Mexico.

Mich. Miner, vol. 5, no. 2, pp. 13–15, figs. 1–5, 1903.

Describes the character, geologic occurrence, and mining of the Cretaceous coal beds.

1028 **Riggs** (Elmer S.). Brachiosaurus altithorax, the largest known dinosaur.

Am. Jour. Sci., 4th ser., vol. 15, pp. 299–306, figs. 1–7, 1903.

Gives a description of this Jurassic fossil and discusses its relationships.

1029 —— Structure and relationships of Opisthocœlian dinosaurs. Part I. Apatosaurus Marsh.

Field Col. Mus., Geol. ser., vol. 2, pp. 165–196, pls. 46–53, figs. 1–18, 1903.

1030 **Riggs** (Elmer S.). The vertebral column of Brontosaurus.
Science, new ser., vol. 17, pp. 393–394, 1903.

1031 —— The use of pneumatic tools in the preparation of fossils.
Science, new ser., vol. 17, pp. 747–749, 1903.

1032 **Robbins** (F.). Ore occurrence at Leadville, Colo.
Mg. & Sci. Press, vol. 86, p. 168, 1903.
Describes the general stratigraphy of the region and the occurrence of the ore bodies.

1033 **Roberts** (Milnor). Note on the action of frost on soil.
Jour. Geol., vol. 11, pp. 314–317, figs. 1–4, 1903.

1034 **Rockstroh** (Edwin). Recent earthquakes in Guatemala.
Nature, vol. 67, pp. 271–272, 1903.

1035 **Rogers** (Austin F.). The minerals of the Joplin, Mo., lead and zinc district.
Abstract: N. Y. Acad. Sci., Ann., vol. 15, pp. 60–61, 1903.

1036 **Rohn** (Oscar). The Baraboo iron range [Wisconsin].
Eng. & Mg. Jour., vol. 76, pp. 615–617, ill., 1903.
Describes the general geology of the area and the occurrence and character of the iron ore.

1037 **Rollet de l'Isle et Giraud, Lacroix** (A.). Sur l'éruption de la Martinique.
See Lacroix (A.), Rollet de l'Isle et Giraud (J.), 727.

1038 **Rowe** (Jesse Perry). Some volcanic ash beds of Montana.
Mont. Univ., Bull. no. 17 (Geol. ser. no. 1), 32 pp., 9 pls., 1903.
Discusses the origin of the volcanic ash of Montana; describes its composition and properties and distribution in the State by counties; gives a list and figures of fossil leaves from the ash of Missoula County.

1039 —— Some Montana coal fields.
Am. Geol., vol. 32, pp. 369–380, pls. 31–32, 1903.
Describes the bituminous and lignite coal resources of Montana and the geographic distribution, by counties, of coal deposits.

1040 **Rowley** (R. R.). See Greene (George K.), 480–485.

1041 **Ruddy** (C. A.), **Landes** (Henry) and. Coal deposits of Washington.
See Landes (Henry) and Ruddy (C. A.), 753.

1042 **Ruedemann** (Rudolf). The Cambric Dictyonema fauna in the slate belt of eastern New York.
N. Y. State Mus., Bull. 69, pp. 934–958, pls. 1–4, 1903.
Describes occurrence, character, geologic position, and paleontology of Upper Cambrian strata in Rensselaer County, New York, and discusses the relations of the Dictyonema beds of Scandinavia, Great Britain, and North America, and the bearing of the latter upon paleogeography.

1043 **Ruedemann** (Rudolf). Noetling on the morphology of the pelecypods.

Am. Geol., vol. 31, pp. 34–40, pl. 3, 1903.

Gives a summary of Noetling's views on the "law of torsion" in pelecypod shells and the relations of the animal and the position of its shell.

1044 —— Professor Jaekel's theses on the mode of existence of Orthoceras and other cephalopods.

Am. Geol., vol. 31, pp. 199–217, 1903.

Gives a translation of Professor Jaekel's theses and some of the discussion following (Zeitschrift der Deutschen geologischen Gesellschaft, 54 Bd., 2 Heft, Protokolle, pp. 67–101, 1902), and discusses these propositions. Includes "Annotations" by John M. Clarke.

1045 —— **Clarke** (John M.). Guelph fauna in the State of New York.

See Clarke (J. M.) and Ruedemann (Rudolf), 204.

1046 —— See Clarke (J. M.), 203.

1047 **Ruhm** (H. D.). The present and the future of the Mount Pleasant phosphate field.

Eng. Assoc. South., Trans., 1902, vol. 13, pp. 42–64 [1903].

Describes discovery, occurrence, and production of phosphate rock in the Mount Pleasant phosphate field of Tennessee.

1048 **Russell** (Israel C.). Notes on the geology of southwestern Idaho and southeastern Oregon.

U. S. Geol. Surv., Bull. no. 217, 83 pp., 18 pls., 2 figs., 1903.

Describes climatic conditions, topography, hydrography, recent and Tertiary volcanic formations, and the geologic structure of this region, and discusses conditions of origin and accumulation of petroleum.

1049 —— Preliminary report on artesian basins in southwestern Idaho and southeastern Oregon.

U. S. Geol. Surv., Water-Supply and Irrigation Paper no. 78, 51 pp., 2 pls., 3 figs., 1903.

Includes a short account of the general geology of the region.

1050 —— Volcanic eruptions on Martinique and St. Vincent.

Smith. Inst., Ann. Rept. for 1902, pp. 331–349, pls. 1–11, 1903.

Reprinted by permission, after revision by the author, from the National Geographic Magazine, vol. 13, no. 12, December, 1902. See no. 922 of U. S. Geol. Surv., Bull. no. 221, 1903.

1051 —— Glacier cornices.

Jour. Geol., vol. 11, pp. 783–785, fig. 1, 1903.

Describes glacier cornices and discusses their origin.

1052 —— The Pelé obelisk.

Science, new ser., vol. 18, pp. 792–795, 1903.

S.

1053 **Salisbury** (Rollin D.). The surface formations in southern New Jersey.

N. J. Geol. Surv., Ann. Rept. for 1900, pp. 33–40, 1901.

Describes the character and occurrence of the surface formations of pre-Pleistocene and Pleistocene ages in southern New Jersey.

1054 —— and **Blackwelder** (Eliot). Glaciation in the Bighorn Mountains.

Jour. Geol., vol. 11, pp. 216–223, figs. 1–2, 1903.

Describes distribution of glaciers in the region, and character, occurrence, and age of the glacial deposits.

1055 **Sapper** (Karl). Der Ausbruch des Vulkans Santa Maria in Guatemala (Oktober, 1902).

Centralbl. f. Min., pp. 33–44, fig. 1; pp. 65–70, figs. 1–3, 1903.

Describes phenomena connected with the volcanic eruption of Santa Maria in Guatemala in October, 1902.

1056 —— Weitere Mittheilungen über den Ausbruch des Vulkans St. Maria in Guatemala.

Centralbl. f. Min., pp. 71–72, 1903.

Gives further observations upon the eruption of the volcano St. Maria in Guatemala.

1057 —— Die jüngsten Ereignisse am Vulkan Izalco (Salvador).

Centralbl. f. Min., pp. 103–111, 1 fig., 1903.

Describes volcanic phenomena in Salvador.

1058 —— Ein Besuch der Insel Grenada.

Centralbl. f. Min., pp. 182–186, 1903.

Gives observations upon volcanic deposits of this island.

1059 —— Bericht über einen Besuch von St. Vincent.

Centralbl. f. Min., pp. 248–258, figs. 1–5, 1903.

Gives observations upon the geology and volcanic phenomena of St. Vincent.

1060 —— Zur Kenntniss der Insel S. Lucia in Westindien.

Centralbl. f. Min., pp. 273–278, figs. 1–2, 1903.

Gives observations upon the geology and sulphur springs of the island.

1061 —— Ein Besuch der Insel Montserrat (Westindien).

Centralbl. f. Min., pp. 279–283, 1 fig., 1903.

Gives observations upon the geology of the island.

1062 —— Ein Besuch von Dominica.

Centralbl. f. Min., pp. 305–314, figs. 1–3, 1903.

Gives observations upon geologic features of the island.

1063 —— Ein Besuch von S. Eustatius und Saba.

Centralbl. f. Min., pp. 314–318, figs. 1–3, 1903.

Gives observations upon the geology of these islands.

1064 —— Ein Besuch von Guadeloupe.

Centralbl. f. Min., pp. 319–323, figs. 1–2, 1903.

Gives observations upon the geology and fumaroles of the island.

1065 **Sapper** (Karl). Ein Besuch von Martinique.

Centralbl. f. Min., pp. 337–358, figs. 1–7, 1903.

Describes observations upon the geology of the island and the phenomena connected with the eruptions of Mont Pelé.

1066 —— Der Krater der Soufrière von St. Vincent.

Centralbl. f. Min., pp. 369–373, figs. 1–2, 1903.

Describes the crater of the Soufrière of St. Vincent.

1067 —— Ein Besuch der Inseln Nevis und S. Kitts (S. Christopher) [West Indies].

Centralbl. f. Min., pp. 384–387, figs. 1–2, 1903.

Gives observations upon the geologic formations of the island.

1068 **Sardeson** (Frederick W.). Observations on the genus Romingeria, by Charles E. Beecher.

Am. Geol., vol. 32, pp. 260–261, 1903.

1069 —— The phylogenic stage of the Cambrian gastropoda.

Jour. Geol., vol. 11, pp. 469–492, pls. 1–2, 1903.

1070 **Sarle** (Clifton J.). A new Eurypterid fauna from the base of the Salina of western New York.

N. Y. State Mus., Bull. 69, pp. 1080–1108, pls. 6–26, 1903.

1071 **Savage** (T. E.). Geology of Tama County [Iowa].

Iowa Geol. Surv., vol. 13, pp. 185–253, figs. 19–31, 1903.

Describes topography and drainage, the character, occurrence, and geologic relations of Devonian and Carboniferous strata and Glacial and post-Glacial deposits, and the economic resources.

1072 —— The Toledo lobe of Iowan drift.

Iowa Acad. Sci., Proc. for 1902, vol. 10, pp. 123–129, 1903.

Describes the geographic position, physiographic features, and component materials of this portion of the drift sheet, and the distribution of drift deposits in the lobe, and the sequence of geologic events producing them.

1073 **Schaller** (Waldemar T.). Minerals from Leona Heights, Alameda Co., California.

Cal. Univ., Dept. Geol., Bull., vol. 3, pp. 191–217, pl. 19, 1903.

1074 —— Spodumene from San Diego Co., California.

Cal. Univ., Dept. Geol., Bull., vol. 3, pp. 265–275, pls. 25–27, 1903.

Describes occurrence, crystallization, physical properties, and composition.

1075 **Schmeckebier** (Laurence F.). Catalogue and index of the publications of the Hayden, King, Powell, and Wheeler surveys, namely: Geological and Geographical Survey of the Territories, Geological Exploration of the Fortieth Parallel, Geographical and Geological Surveys of the Rocky Mountain region, Geographical Surveys west of the One Hundredth Meridian.

U. S. Geol. Surv., Bull. no. 222, 208 pp., 1903.

1076 **Schmidt** (C.). Ueber vulkanische Asche, gefallen in San Cristobal L. C. (Süd-Mexiko) am 25 Oktober 1902.
Centralbl. f. Min., p. 131, 1903.
Discusses the composition of volcanic ashes.

1077 **Schneider** (Philip F.). Notes on the geology of Onondaga County, N. Y.
Syracuse, N. Y., 47 pp., 1894. (Privately printed.)
Describes the character, occurrence, and geologic relations of the formations of Silurian and Devonian age in this county, and gives observations upon the occurrence of fossils.

1078 —— Limestones in central New York.
Onondaga Acad. Sci., Science ser., no. 1, 16 pp., 1897.
Describes the occurrence, character, and utilization of the limestones in central New York.

1079 —— The Marcellus fault.
Onondaga Acad. Sci., Science ser., no. 2, 7 pp., 1899.
Describes faulting in the vicinity of Marcellus, N. Y.

1080 —— The whetstone industry.
Onondaga Acad. Sci., Proc., vol. 1, pp. 20–31, 1903.
Describes the occurrence and character of the Labrador whetstone in the Portage group in the vicinity of Syracuse, N. Y.

1081 —— The geology of the serpentines of central New York.
Onondaga Acad. Sci., Proc., vol. 1, pp. 110–117, 1903.
Describes the occurrence and petrologic characters of dikes at Syracuse, N. Y.

1082 —— Notes on some eruptive dikes near Ithaca [New York].
Onondaga Acad. Sci., Proc., vol. 1, pp. 130–136, 1903.

1083 **Schottler** (W.). Bemerkung über die in San Cristobal (S.-Mexico) am 25 Okt. 1902 gefallene Asche.
Centralbl. f. Min., pp. 286–289, 1903.
Describes petrographic characters of volcanic ashes from San Cristobal, in southern Mexico.

1084 **Schrader** (Frank Charles) and **Spencer** (Arthur Coe). The geology and mineral resources of a portion of the Copper River district, Alaska.
U. S. Geol. Surv., Special reports, 94 pp., 13 pls., 1901.
See no. 941 of U. S. Geol. Surv., Bull. no. 221.

1085 —— **Mendenhall** (Walter C.) and. Copper deposits of the Mount Wrangell region, Alaska.
See Mendenhall (W. C.) and Schrader (F. C.), 881.

1086 —— **Mendenhall** (Walter C.). The mineral resources of the Mount Wrangell district, Alaska.
See Mendenhall (W. C.) and Schrader (F. C.), 880.

1087 **Schuchert** (Charles). Morse on living brachiopods.

Am. Geol., vol. 31, pp. 112–121, 1903.

Reviews "Observations on living brachiopods," by Edward S. Morse, especially such parts as have a direct bearing on fossil forms. Includes observations on paleozoic forms.

1088 —— The I. H. Harris collection of invertebrate fossils in the United States National Museum.

Am. Geol., vol. 31, pp. 131–135, pl. 11 (por.), 1903.

Gives a sketch of the life of Mr. I. H. Harris and an account of the collection which he accumulated.

1089 —— On the Manlius formation of New York.

Am. Geol., vol. 31, pp. 160–178, 3 figs., 1903.

Discusses stratigraphic position of the Coralline limestone of the New York series and gives notes upon its fauna, with descriptions of some species.

1090 —— On the faunal provinces of the middle Devonic of America and the Devonic coral sub-provinces of Russia, with two paleographic maps.

Am. Geol., vol. 32, pp. 137–162, pls. 20–21, 1903.

Gives a summary of Lebedew's work on the corals of Russia, describes the faunal provinces of the American middle Devonic and relations of their faunas with one another and with the faunas of European provinces, and tabulates the distribution of American corals in the Mississippian and Dakota seas.

1091 —— On new Siluric cystoidea and a new Camarocrinus.

Am. Geol., vol. 32, pp. 230–240, 1903.

1092 —— On the lower Devonic and Ontaric formations of Maryland.

U. S. Nat. Mus., Proc., vol. 26, pp. 413–424, 1903.

Describes character, occurrence, faunal contents, and geologic relationships of Silurian and Devonian strata in Allegany County, Maryland, and vicinity.

1093 —— See Diller (J. S.), 302.

1094 **Seely** (Henry M.). Sketch of the life and work of Charles Baker Adams.

Am. Geol., vol. 32, pp. 1–12, pl. 1 (por.), 1903.

1095 **Sellards** (E. H.). Some new structural characters of Paleozoic cockroaches.

Am. Jour. Sci., 4th ser., vol. 15, pp. 307–315, pls. 7–8, 1903.

Discusses structural features and immature stages, and describes several forms of Carboniferous cockroaches.

1096 —— Codonotheca, a new type of spore-bearing organ from the Coal Measures.

Am. Jour. Sci., 4th ser., vol. 16, pp. 87–95, pl. 8, 1903.

1097 —— Discovery of fossil insects in the Permian of Kansas.

Am. Jour. Sci., 4th ser., vol. 16, pp. 323–324, 1903.

1098 **Shattuck** (George Burbank). The mollusca of the Buda limestone, with an appendix on the corals of the Buda limestone.

U. S. Geol. Surv., Bull. no. 205, 94 pp., 27 pls., 1 fig., 1903.

Gives a short account of the geology of the Buda limestone in Texas and descriptions of the molluscan fauna found therein.

1099 **Sheak** (W. H.), **Blatchley** (W. S.) and. Trenton rock petroleum.

See Blatchley (W. S.) and Sheak (W. H.), 93.

1100 **Shedd** (Solon). The building and ornamental stones of Washington.

Wash. Geol. Surv., vol. 2, Ann. Rept. for 1902, pp. 1–163, pls. 1–22, 1903.

Discusses physical properties required in building stones and describes character, occurrence, and utilization of stone deposits of Washington suitable for building and decorative purposes.

1101 **Sheldon** (George) and **Sheldon** (J. M. Arms). Newly exposed geologic features within the old "8,000 Acre Grant."

New York, 21 pp., 12 pls., 1903. (Private publication.)

Describes peculiar structural features in sand and clay deposits and columnar trap formations and discusses their origin.

1102 **Sheldon** (J. M. Arms), **Sheldon** (George) and. Newly exposed geologic features within the old "8,000 Acre Grant."

See Sheldon (George) and Sheldon (J. M. A.), 1101.

1103 **Sherwin** (R. S.) Notes on the geology of the Antelope Hills [Oklahoma].

Kans. Acad. Sci., Trans., vol. 18, pp. 83–84, 1903.

Gives a brief account of the geology of this region.

1104 —— Notes on the theories of origin of gypsum deposits.

Kans. Acad. Sci., Trans., vol. 18, pp. 85–88, 1903.

Discusses the origin of the gypsum deposits of Kansas and Oklahoma.

1105 **Shimek** (B.). The loess and the Lansing man.

Am. Geol., vol. 32, pp. 353–369, 1903.

Discusses the character of the fossil shells occurring in the loess and their bearing upon the question of the origin of the loess.

1106 —— Living plants as geological factors.

Iowa Acad. Sci., Proc. for 1902, vol. 10, pp. 41–48, pls. 2–13, 1903.

Discusses the action of plants in the disintegration and formation of deposits.

1107 —— See Udden (J. A.), 1220.

1108 **Shimer** (Hervey W.). [Report of] Fall excursions of the Geological Department, Columbia University.

Am. Geol., vol. 31, pp. 62–64, 1903.

Contains notes on the geology and petrology of Manhattan Island and localities in the vicinity of New York City.

1109 **Shimer** (Hervey W.). [Field work at Larrabee's Point, Vermont.]
Am. Geol., vol. 32, pp. 130–131, 1903.

1110 —— [Report of] Columbia University Geological Department.
Am. Geol., vol. 32, pp. 259–260, 1903.
Describes observations in northeastern New Jersey.

1111 **Silver** (L. P.). Petrography of some igneous rocks of the Kettle River mining division, British Columbia.
Ottawa Nat., vol. 17, pp. 85–91, 1903.
Describes their characters and occurrence.

1112 **Simmersbach** (B.). Die Steinkohlengebiete von Pennsylvanien und Westvirginien.
Zeitsch. f. prak. Geol., vol. 11, pp. 413–423, fig. 96, 1903.
Gives a general account of the Appalachian coal field, describing its geographic extent, and the succession, thickness, character, and distribution of the geologic formations.

1113 **Simonds** (Frederic W.). The minerals and mineral localities of Texas.
Tex. Univ., Min. Surv., Bull. no. 5, pp. 3–95, 1902.
Describes characters and occurrences of minerals found in Texas.

1114 **Simpson** (Howard E.). The accretion of flood plains by means of sand bars.
Iowa Acad. Sci., Proc. for 1902, vol. 10, pp. 54–56, 1903.

1115 **Sinclair** (William J.). A preliminary account of the exploration of the Potter Creek cave, Shasta County, California.
Science, new ser., vol. 17, pp. 708–712, 1903.
Describes the situation of the cave, the deposits in it, and the occurrence of vertebrate remains, with a list of the forms identified.

1116 —— Mylagaulodon, a new rodent from the upper John Day of Oregon.
Am. Jour. Sci., 4th ser., vol. 15, pp. 143–144, 1 fig., 1903.
Describes the characters and relations of a new genus and species.

1117 —— A new tortoise from the auriferous gravels of California.
Cal. Univ., Dept. Geol., Bull., vol. 3, pp. 243–248, figs. 1–2, 1903.

1118 —— **Merriam** (John C.) and. The correlation of the John Day and the Mascall.
See Merriam (J. C.) and Sinclair (W. J.), 886.

1119 **Skinner** (W. W.). The underground waters of Arizona—their character and uses.
Ariz. Univ. Agric. Exp. Sta., Bull, no. 46, pp. 273–296, 1 pl., 1903.

1120 **Slosson** (E. E.) and **Moody** (R. B.). The Laramie cement plaster.
Wyo. Univ., Agr. Coll., 10th Ann. Rept., 18 pp., 1 pl., 1900.
Describes the occurrence of gypsum beds and the composition and manufacture of cement plaster.

1121 **Slosson** (E. E.), **Knight** (W. C.) and. The Bonanza, Cottonwood, and Douglas oil fields.

See Knight (W. C.) and Slosson (E. E.), 697.

1122 **Smallwood** (W. M.) and **Hopkins** (T. C.). A discussion of the origin of some anticlinal folds near Meadville, Pennsylvania.

Syracuse Univ., Bull., ser. 4, no. 1, pp. 18–24, 1903.

Describes drainage and geological structure of this region.

1123 **Smith** (Alva J.). Geology of Lyon County, Kansas.

Kans. Acad. Sci., Trans., vol. 18, pp. 99–103, 1903.

Describes the stratigraphy.

1124 **Smith** (D. T.). A geological reconnoissance of the region of the upper main Walker River, Nevada.

Abstract: Eng. & Mg. Jour., vol. 75, p. 154, 1903; Jour. Geol., vol. 11, pp. 94–95, 1903.

1125 **Smith** (Eugene A.). Carboniferous fossils in 'Ocoee' slates in Alabama.

Science, new ser., vol. 18, pp. 244–246, 1903.

Discusses the determinations of the age of the Ocoee slates and related formations and the occurrence in them of Carboniferous plants in Clay County, Alabama.

1126 —— The Portland cement materials of central and southern Alabama.

Cement Resources of Alabama. 58th Cong., 1st sess., Sen. Doc. no. 19, pp. 12–23, map, 1903.

Describes character and distribution of Cretaceous and Tertiary limestones suitable for use in the manufacture of Portland cement. Includes a map showing the distribution of these limestones and the coal of northern Alabama.

1127 —— and **Aldrich** (Truman H.). The Grand Gulf formation.

Science, new ser., vol. 18, pp. 20–26, 1903.

Discusses stratigraphic position of the Grand Gulf formation.

1128 **Smith** (Frank B.). The Frank disaster [Alberta].

Can. Mg. Rev., vol. 22, pp. 102–103, 1903.

Describes the landslide and attendant disasters at Frank, Alberta.

1129 **Smith** (George). [In discussion of paper by S. F. Emmons, "The secondary enrichment of ore-deposits."]

Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 1055–1059, 1903.

Discusses formation of certain ore-deposits.

1130 **Smith** (George Otis). The geology of Mount Rainier.

Mazama, vol. 2, no. 1, pp. 18–24, 1900.

Describes geologic history of Mount Rainier and the character and occurrence of its igneous rocks.

1131 **Smith** (George Otis). Ellensburg folio, Washington.

U. S. Geol. Surv., Geol. Atlas of U. S., folio no. 86, 1903.

Describes geographic features, drainage and water supply of the Ellensburg quadrangle, the geologic history of the Cascade Mountains and of the Ellensburg quadrangle, and the character and occurrence of Miocene strata and igneous rocks, and discusses character and origin of structural and physiographic features and economic resources of the quadrangle.

1132 —— Geology and physiography of central Washington.

U. S. Geol. Surv., Professional Paper no. 19, pp. 9–39, pls. 1–7, fig. 1, 1903.

Reviews previous work upon the region, describes the character, extent, and relations of igneous rocks and sedimentary strata of pre-Eocene, Eocene, and Miocene age, the geologic history and structure, and physiographic features and history.

1133 —— Gold mining in central Washington.

U. S. Geol. Surv., Bull. no. 213, pp. 76–80, 1903.

Describes occurrence of gold in gravel deposits and quartz veins, and the mining operations in the district.

1134 —— Anticlinal mountain ridges in central Washington.

Jour. Geol., vol. 11, pp. 166–177, fig. 1, 1903.

Reviews previous work in the area and describes its geological structure.

1135 —— [In discussion of paper by W. P. Jenney, "The mineral crest, or the hydrostatic level attained by the ore-depositing solutions in certain mining districts of the Great Salt Lake Basin."]

Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 1060–1062, 1903.

Gives geologic observations bearing upon the subject of the paper discussed.

1136 —— Abandoned stream gaps in northern Washington.

Abstract: Science, new ser., vol. 17, pp. 387–388, 1903.

1137 **Smith** (James Perrin). The Carboniferous ammonoids of America.

U. S. Geol. Surv., Mon., vol. 42, 211 pp., 29 pls., 1903.

Reviews briefly the occurrence of ammonoids in the different Carboniferous formations of America, gives tables of the correlation of Carboniferous formations, discusses the classification and phylogeny, and describes and figures American genera and species.

1138 **Smith** (W. S. Tangier). Hartville folio, Wyoming.

U. S. Geol. Surv., Geol. Atlas of U. S., folio no. 91, 1903.

Describes geographic and topographic features, character, and occurrence of igneous rocks and sedimentary deposits of Algonkian, Carboniferous, Juratrias, Cretaceous, Tertiary, and Quaternary systems, the geologic history and economic products.

1139 **Smith** (W. S. Tangier). Lead and zinc deposits of the Joplin district, Missouri-Kansas.

U. S. Geol. Surv., Bull. no. 213, pp. 197–204, 1903.

Describes briefly the stratigraphy and geologic structure of the region and the character, occurrence, and origin of the ores.

1140 —— **Ulrich** (E. O.) and. Lead, zinc, and fluorspar deposits of western Kentucky.

See Ulrich (E. O.) and Smith (W. S. T.), 1223.

1141 **Smith** (William G.). Soil survey from Raleigh to Newbern, N. C.

U. S. Dept. Agric., Field Oper. Div. Soils, 1900, 2d Rept., pp. 187–205, pls. 8–15, 1901.

Includes observations on physiographic features.

1142 —— and **Bennett** (Frank, jr.). Soil survey of the Lebanon area, Pennsylvania.

U. S. Dept. Agric., Field Oper. Bur. Soils, 1901, 3d Rept., pp. 149–171, pls. 17–20, 1902.

Includes a brief account of the physiography and geology.

1143 —— and **Martin** (J. O.). Soil survey of Harford County, Maryland.

U. S. Dept. Agric., Field Oper. Bur. Soils, 1901, 3d Rept., pp. 211–237, 1902.

Includes a short account of the physiography and geology.

1144 —— Soil survey of the Toledo area, Ohio.

U. S. Dept. Agric., Field Oper. Bur. Soils, 1902, 4th Rept., pp. 383–402, pls. 21–23, 1903.

Includes a brief account of the physiography and geology.

1145 —— Soil survey of the Columbus area, Ohio.

U. S. Dept. Agric., Field Oper. Bur. Soils, 1902, 4th Rept., pp. 403–423, pl. 24, 1903.

Includes a short account of the physiography and geology.

1146 —— and **Carter** (William T., jr.). Soil survey of the Smedes area, Mississippi.

U. S. Dept. Agric., Field Oper. Bur. Soils, 1902, 4th Rept., pp. 325–348, pls. 16–18, 1903.

Includes a short account of the physiography and geology.

1147 **Smyth** (C. H., jr.). The Rossie lead veins [New York].

School of Mines Quart., vol. 24, pp. 421–429, 1 fig., 1903.

Describes the character and occurrence of the rocks and galena-bearing veins, and discusses the origin and age of the vein-filling materials.

1148 **Spencer** (Arthur Coe.) Pacific mountain system in British Columbia and Alaska.

Geol. Soc. Am., Bull., vol. 14, pp. 117–132, pls. 8–13, 1903.

Describes physiographic features and discusses their origin.

1149 **Spencer** (Arthur Coe). Mineral resources of the Encampment copper region, Wyoming.

U. S. Geol. Surv., Bull. no. 213, pp. 158–162, 1903.

Gives an account of the general geology of this region and the character and occurrence of the deposits of copper ores.

1150 —— Reconnoissance examination of the copper deposits at Pearl, Colo.

U. S. Geol. Surv., Bull. no. 213, pp. 163–169, 1903.

Gives a brief account of the geography and geology of this region and describes the mining developments.

1151 —— Manganese deposits of Santiago, Cuba.

U. S. Geol. Surv., Bull. no. 213, pp. 251–255, 1903.

Describes briefly the geologic structure of the region and the occurrence and probable output of manganese ores.

1152 **Spencer** (Joseph William Winthrop). On the geological relationship of the volcanoes of the West Indies.

Victoria Inst., Jour. Trans., vol. 35, pp. 198–207, 1 fig., 1903.

Discusses physiographic features and changes of the West Indies islands and the submerged plateau upon which they rest, the place of their igneous formations in geologic history and the evidences of the geologic age of the volcanic activity and its relations to physical changes in the Antillean region.

1153 —— Geological age of the West Indian volcanic formations.

Am. Geol., vol. 31, pp. 48–51, 1 fig., 1903.

Discusses the geologic history of the region.

1154 —— Submarine valleys off the American coast and in the North Atlantic.

Geol. Soc. Am., Bull., vol. 14, pp. 207–226, pls. 19–20, figs. 1–2, 1903.

Describes the submerged Atlantic coastal plain from Cape Hatteras to Newfoundland and the channels traversing it, discusses geological data and evidences of the age of the submerged valleys and describes submerged valleys of the North Atlantic and adjacent Arctic basins.

1155 **Spurr** (Josiah Edward). Descriptive geology of Nevada south of the Fortieth Parallel and adjacent portions of California.

U. S. Geol. Surv., Bull. no. 208, 229 pp., 8 pls., 25 figs., 1903.

Describes physiographic features, character and occurrence of sedimentary and igneous rocks and ore deposits and structure of the region, including résumé of previous publications and unpublished data furnished by C. D. Walcott, H. W. Turner, F. B. Weeks, R. B. Rowe, G. H. Girty, and E. O. Ulrich.

1156 —— The determination of the feldspars in thin section.

Am. Geol., vol. 31, pp. 376–383, 1903.

1157 —— Ore deposits of Tonopah and neighboring districts, Nevada.

U. S. Geol. Surv., Bull. no. 213, pp. 81–87, 1903.

Describes the history of the devolopment of the field, the topography, general geology, and character and occurrence of the ore deposits.

1158 **Spurr** (Josiah Edward). The ore deposits of Tonopah, Nevada (preliminary report).

U. S. Geol. Surv., Bull. no. 219, 34 pp., pl. 1, figs. 1–4, 1903.

Gives a brief history of the discovery and development of this mining district, and describes the geologic structure and history of the region, the periods and nature of mineralization, and the occurrence of the ores and their relation to the geologic structure.

1159 —— Relation of rock segregation to ore deposition.

Eng. & Mg. Jour., vol. 76, pp. 54–55, 1903.

Discusses the origin of ore deposits.

1160 —— The ore deposits of Tonopah, Nevada.

Eng. & Mg. Jour., vol. 76, pp. 769–770, ill., 1903.

Describes the geologic structure of the region and the occurrence of the ore deposits of precious metals.

1161 —— A consideration of igneous rocks and their segregation or differentiation as related to the occurrence of ores.

Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 288–340, 1903.

Discusses the relations of igneous rocks and ore deposits, and the origin of the latter.

1162 —— [In discussion of paper by Waldemar Lindgren, "The geological features of the gold production of North America."]

Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 1081–1083, 1903.

Discusses the age of certain gold deposits in Alaska.

1163 —— The application of geology to mining.

Intern. Mg. Cong., Proc. 5th sess., pp. 80–86 [1903].

1164 —— [Genetic classification of ore deposits.]

Abstract: Science, new ser., vol. 17, p. 274, 1903.

1165 —— The relation of faults to topography.

Abstract: Science, new ser., vol. 17, p. 792, 1903.

1166 **Stanton** (Timothy W.). A new fresh-water molluscan faunule from the Cretaceous of Montana.

Am. Phil. Soc., Proc., vol. 42, pp. 188–199, pl. 4, 1903.

Discusses the stratigraphic horizon of this faunule, and the occurrence of Cretaceous formations and their correlation, and describes six new species of fresh-water mollusks.

1167 —— Alpheus Hyatt.

Washington Acad. Sci., Proc., vol. 5, pp. 389–391, 1903.

1168 —— See Diller (J. S.), 302.

1169 —— See Hyatt (Alpheus), 625.

1170 —— See Washburne (Chester), 1265.

1171 **Starbird** (H. B.). Secondary enrichment in arid regions.

Eng. & Mg. Jour., vol. 75, pp. 702–703, 1903.

Describes occurrence and origin of gold and copper ores.

1172 **Stead** (Geoffrey). Notes on the surface geology of New Brunswick.

New Brunswick Nat. Hist. Soc., Bull. no. 21 (vol. 5, pt. 1), pp. 5–13, 1903.

Describes the process of formation of shore deposits along the coast of New Brunswick.

1173 **Steel** (A. A.). The ore deposits of La Cananea [Mexico].

Eng. & Mg. Jour., vol. 76, pp. 458–460, ill., 1903.

Gives observations upon the geology and the character and occurrence of the copper ore deposits.

1174 **Steele** (James H.). The Joplin zinc district of southwestern Missouri.

Colo. Sch. Mines, Bull., vol. 1, pp. 43–50, ill., 1900.

Gives observations upon the geology and describes the occurrence of the ores and the mining operations.

1175 **Sternberg** (Charles H.). Experiences with early man in America.

Kans. Acad. Sci., Trans., vol. 18, pp. 89–93, 1903.

Describes association of human relics with fossil bones of animals and discusses evidence as to their age.

1176 —— The Permian life of Texas.

Kans. Acad. Sci., Trans., vol. 18, pp. 94–98, 1903.

Describes the occurrence of fossil remains and physical characters of the Permian Red Beds in Baylor County, Texas.

1177 —— Elephas columbi and other mammals in the swamps of Whitman County, Washington.

Science, new ser., vol. 17, pp. 511–512, 1903.

Describes the occurrence of mammalian remains.

1178 —— Notes on the Judith River group.

Science, new ser., vol. 17, pp. 870–872, 1903.

Discusses the occurrence of vertebrate fossils and the stratigraphic position of the Judith River beds.

1179 **Stevens** (Blamey). Geology of some copper deposits in Alaska.

Eng. & Mg. Jour., vol. 75, p. 782, figs. 1–2, 1903.

1180 —— Relation of rock segregation to ore deposition.

Eng. & Mg. Jour., vol. 76, p. 574, 1903.

1181 **Stevens** (E. A.). Basaltic zones as guides to ore-deposits in the Cripple Creek district, Colorado.

Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 686–698, figs. 1–4, 1903.

Describes the character and occurrence of igneous rocks and the relations of the dikes, fissures, and ore-deposits.

1182 **Stevenson** (John J.). Lower Carboniferous of the Appalachian basin.

Geol. Soc. Am., Bull., vol. 14, pp. 15–96, 1903.

Describes occurrence, stratigraphy, lithologic characters and geologic relations of Lower Carboniferous formations in the Appalachian region and discusses their nomenclature and correlation, and the physiographic conditions prevailing during their deposition.

1183 —— J. Peter Lesley.

Science, new ser., vol. 18, pp. 1–3, 1903.

1184 —— Joseph Le Conte (obituary).

Abstract: N. Y. Acad. Sci., Ann., vol. 14, pp. 150–151, 1902.

1185 **Stevenson** (Robert). The deposition of ores from an igneous magma.

Eng. & Mg. Jour., vol. 76, p. 882, 1903.

1186 **Stewart** (Alban). Teleosts of the Upper Cretaceous.

Kans. Univ. Geol. Surv., vol. 6, pp. 257–390, pls. 33–73, 1900.

1187 **Stewart** (John), **Gardner** (Frank D.) and. A soil survey in Salt Lake Valley, Utah.

See Gardner (F. D.) and Stewart (John), 432.

1188 **Stoess** (P. C.). The Kayak coal and oil fields of Alaska.

Mg. & Sci. Press, vol. 87, p. 65, 1903.

Describes the general geology of the region and the occurrence of coal and petroleum.

1189 **Stone** (G. H.). [Discovery of coal on Turkey Creek, Colorado.]

Am. Geol., vol. 32, p. 132, 1903.

1190 **Storms** (W. H.). Some structural features of the California gold belt.

Mg. & Sci. Press, vol. 87, pp. 112, 129, 149, 165, 183, 202, 216–217, ill., 1903.

Describes the character and occurrence of the lodes and veins yielding gold ore.

1191 **Stose** (George W.). The structure of a part of South Mountain, Pennsylvania.

Abstract: Science, new ser., vol. 17, p. 387, 1903.

T.

1192 **Taff** (Joseph A.). Tishomingo folio, Indian Territory.

U. S. Geol. Surv., Geol. Atlas of U. S., folio no. 98, 1903.

Describes geography, physiography, general relations, pre-Cambrian igneous rocks, Cambrian, Ordovician, Siluro-Devonian, Carboniferous and Cretaceous sedimentary rocks and Quaternary deposits, geologic structure of the Arbuckle Mountain region, and the mineral resources.

1193 **Talbot** (Mignon). A contribution to the list of the fauna of the Stafford limestone of New York.

Am. Jour. Sci., 4th ser., vol. 16, pp. 148–150, 1903.

1194 **Tarr** (Ralph S.). New physical geography.

New York, The MacMillan Company, xiii, 457 pp., 568 figs., 1903.

1195 —— Post-Glacial and Inter-Glacial (?) changes of level at Cape Ann, Massachusetts.

Harvard Coll. Mus. Comp. Zool., Bull., vol. 42, pp. 181–191, pls. 1–13, 1903.

Describes physiographic features and discusses evidences of changes of level.

1196 **Taylor** (Frank Bursley). The correlation and reconstruction of recessional ice borders in Berkshire County, Massachusetts.

Jour. Geol., vol. 11, pp. 323–364, figs. 1–10, 1903.

Describes topographic and drainage features and moraines, and discusses the evidences as to the movements of the ice sheet and general relations of the ice front to the land relief.

1197 —— Studies in the glaciation of the Berkshire Hills, Massachusetts.

Abstract: Science, new ser., vol. 17, p. 225, 1903; Sci. Am. Suppl., vol. 55, p. 22666, 1903.

1198 **Taylor** (F. W.) and **Rice** (Thomas D.). Soil survey of the Abbeville area, South Carolina.

U. S. Dept. Agric., Field Oper. Bur. Soils, 1902, 4th Rept., pp. 273–289, 1903.

Includes a short account of the physiography and geology.

1199 —— **Bonsteel** (Jay A.) and. Soil survey of the Salem area, New Jersey.

See Bonsteel (J. A.) and Taylor (F. W.), 105.

1200 —— **Rice** (Thomas D.) and. Soil survey of the Darlington area, South Carolina.

See Rice (T. D.) and Taylor (F. W.), 1012.

1201 **Teggart** (Frederick J.). Literature available in the [Mechanics' Institute] Library [San Francisco, California] on petroleum with some references on asphaltum.

Mechanics' Inst. Lib., San Francisco, Cal., Tech. Ref. List no. 1, 24 pp., 1903.

1202 **Thierry** (—). Sur l'éruption volcanique du 8 mai à la Martinique.

Acad. des Sci. [Paris], Compt. rend., vol. 135, pp. 71–72, 1902.

Describes phenomena witnessed during an eruption of Mont Pelé.

1203 **Tight** (W. G.). Drainage modifications in southeastern Ohio and adjacent parts of West Virginia and Kentucky.

U. S. Geol. Surv., Professional Paper no. 13, 111 pp., 17 pls., 1 fig., 1903.

Discusses the present drainage of the region under consideration, the pre-Glacial drainage of adjacent regions, the general topographic features and their relation to the Tertiary peneplain, the characters of the present river valleys, the reconstruction of the old drainage system, relations of present and former drainage systems to one another and to the geologic structure, and the geologic events which caused the drainage changes.

1204 **Titcomb** (H. A.). The Camp Bird gold mine and mills [Colorado].

School of Mines Quart., vol. 24, pp. 56–67, figs. 1–7, 1902.

Gives a general account of the geology and the occurrence of the gold ore deposits and of the mining operations.

1205 **Todd** (James E.). Concretions and their geological effects.

Geol. Soc. Am., Bull., vol. 14, pp. 353–368, pls. 49–53, 1903.

Discusses character, occurrence, and modes of growth of concretions and their influence in producing topographic forms.

1206 —— Building stones of South Dakota.

Stone, vol. 26, pp. 20–27, ill., 1903.

Describes the character and geologic occurrence of building stones.

1207 —— A newly discovered rock at Sioux Falls, South Dakota.

Stone, vol. 27, pp. 46–48, 1903.

Describes the occurrence and character of an igneous rock discovered in this vicinity.

1208 —— Olivet folio, South Dakota.

U. S. Geol. Surv., Geol. Atlas of U. S., folio no. 96, 1903.

Describes geography and topography, general geology, character and occurrence of Algonkian, Cretaceous and Quaternary deposits, geologic history, economic and water resources.

1209 —— Parker folio, South Dakota.

U. S. Geol. Surv., Geol. Atlas of U. S., folio no. 97, 1903.

Describes geography, general geology, and character and occurrence of Algonkian and Cretaceous strata and Quaternary deposits, the geologic history and economic resources, including underground waters.

1210 —— Mitchell folio, South Dakota.

U. S. Geol. Surv., Geol. Atlas of U. S., folio no. 99, 1903.

Describes geography, general geology, the character and occurrence of deposits belonging to the Algonkian, Cretaceous, and Quaternary systems, the geologic history and economic resources, more particularly the underground waters.

1211 —— and **Hall** (C. M.). Alexandria folio, South Dakota.

U. S. Geol. Surv., Geol. Atlas of U. S., folio no. 100, 1903.

Describes geography, general geology, Algonkian, Cretaceous and Quaternary deposits, the geologic history, and economic and artesian water resources of the Alexandria quadrangle.

1212 **Todd** (James E.). See Winchell (N. H.), 1342.

1213 **Transeau** (Edgar N.). On the geographic distribution and ecological relations of the bog plant societies of northern North America.

Bot. Gaz., vol. 36, pp. 401–420, figs. 1–3, 1903.

Includes a discussion of pre-Glacial distribution and Glacial and later migrations of these plant societies.

1214 **Turner** (Henry W.). Post-Tertiary elevation of the Sierra Nevada.

Geol. Soc. Am., Bull., vol. 13, pp. 540–541, pl. 58, 1903.

Discusses the age of the Sierra Nevada uplift.

1215 —— The copper-deposits of the Sierra Oscura, New Mexico.

Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 678–681, fig. 1, 1903.

Describes the geographic features and geologic structure of the region and the occurrence of copper-bearing reefs.

1216 —— The Cretaceous auriferous conglomerate of the Cottonwood mining district, Siskiyou County, California.

Eng. & Mg. Jour., vol. 76, pp. 653–654, ill., 1903.

Discusses the character, occurrence, and geological relations of the rock formations, and the source of the gold contained in the conglomerate.

1217 —— Notes on contact-metamorphic deposits in the Sierra Nevada Mountains.

Am. Inst. Mg. Engrs., Trans. (New York meeting, October, 1903), 2 pp.

Describes occurrences of deposits additional to those noted by Mr. Lindgren (Am. Inst. Mg. Engrs., Trans., vol. 31, pp. 230–231).

1218 —— Observations on Mother Lode gold deposits, California. [In discussion of paper of W. A. Prichard.]

Am. Inst. Mg. Engrs., Trans. (New York meeting, October, 1903), 2 pp.

Discusses the time-relations of the diorite intrusions and the fissuring.

1219 **Tyrrell** (J. B.). A peculiar artesian well in the Klondike.

Eng. & Mg. Jour., vol. 75, p. 188, 1 fig, 1903.

Describes geologic structure of the region and the conditions producing the artesian flow of water.

U.

1220 **Udden** (Johan August). Geology of Mills and Fremont counties [Iowa].

Iowa Geol. Surv., vol. 13, pp. 123–183, pls. 4–7, 1903.

Describes topography and drainage, character, occurrence and geologic relations of Carboniferous and Cretaceous strata and surficial deposits, and economic resources. Includes a report by Prof. B. S. Shimek on the fossils from the loess of these counties.

1221 —— Foraminiferal ooze in the Coal Measures of Iowa.

Jour. Geol., vol. 11, pp. 283–284, 1903.

1222 **Udden** (Johan August). Note to the article on "Foraminiferal ooze in the Coal Measures of Iowa."

Jour. Geol., vol. 11, p. 430, 1903.

Notes the occurrence of a bed of foraminiferal ooze in the upper Carboniferous of Texas.

1223 **Ulrich** (Edward Oscar) and **Smith** (W. S. Tangier). Lead, zinc, and fluorspar deposits of western Kentucky.

U. S. Geol. Surv., Bull. no. 213, pp. 205–213, 1903.

Describes the mining development and geologic structure of the region and the character and occurrence of the veins and vein minerals.

1224 —— **Hayes** (C. Willard) and. Columbia folio, Tennessee.

See Hayes (C. W.) and Ulrich (E. O.), 533.

1225 **United States Geological Survey**. Geology, etc., of the Coosa Valley, Alabama.

56th Cong., 2d sess., Senate Doc. no. 65, 4 pp., 1901.

A letter from the Director of the United States Geological Survey submitting a brief sketch of the geology and natural resources of the Coosa Valley, in the State of Alabama.

1226 **Upham** (Warren). Valley loess and the fossil man of Lansing, Kansas.

Am. Geol., vol. 31, pp. 25–34, 1903.

Discusses distribution and origin of loess deposits and the evidences for the age of the fossiliferous remains found near Lansing, Kansas.

1227 —— The life and work of Professor Charles M. Hall.

Am. Geol., vol. 31, pp. 195–198, pl. 13 (por.), 1903.

1228 —— How long ago was America peopled?

Am. Geol., vol. 31, pp. 312–315, 1903.

Discusses time estimates of Glacial and post-Glacial periods and evidences of antiquity of man in America.

1229 —— Glacial Lake Nicolet and the portage between the Fox and Wisconsin rivers.

Am. Geol., vol. 32, pp. 105–115, 1903.

1230 —— The antiquity of the fossil man of Lansing, Kansas.

Am. Geol., vol. 32, pp. 185–187, 1903.

1231 —— The glacial lakes Hudson-Champlain and St. Lawrence.

Am. Geol., vol. 32, pp. 223–230, 1903.

1232 —— Glacial Lake Jean Nicolet.

Am. Geol., vol. 32, pp. 330–331, 1903.

As the name Lake Nicollet had been previously used by Winchell, the writer amends his name Lake Nicolet to the form given above.

1233 —— Geology of Prairie Island [Minnesota].

Memoirs of Exploration in the Basin of the Mississippi, vol. 6, Minnesota, pp. 34–38, 1903.

1234 —— The past and future of Niagara Falls.

State Reservation at Niagara, Comm. 19th Ann. Rept., pp. 231–254, 1903.

V.

1235 **Van Diest** (P. H.). A mineralogical mistake.

Colo. Sci. Soc., Proc., vol. 6, pp. 150–156, 1 pl. [1902].

Contains observations on occurrence of rocks and ores, and describes the efforts to find tin in the Greenhorn Mountains of Colorado.

1236 **Van Hise** (Charles Richard). Geological work in the Lake Superior region.

Lake Sup. Mg. Inst., Proc. for 1902, vol. 8, pp. 62–69 [1903].

Discusses the difficulties of geologic work in this region and gives an historical review of the work that has been done.

1237 —— Powell as an explorer.

Wash. Acad. Sci., Proc., vol. 5, pp. 105–112, 1903.

1238 —— Genetic classification of ore deposits.

Abstract: Science, new ser., vol. 17, pp. 542–543, 1903.

1239 **Van Ingen** (Gilbert). A method of facilitating photography of fossils.

Abstract: N. Y. Acad. Sci., Ann., vol. 14, pp. 115–116, 1902.

1240 —— and **Clark**, (P. Edwin). Disturbed fossiliferous rocks in the vicinity of Rondout, N. Y.

N. Y. State Mus., Bull. 69, pp. 1176–1227, pls. 1–13, 1903.

Describes location, stratigraphy, paleontology, and structural features of Silurian and Devonian strata in the city of Rondout, New York, and its vicinity.

1241 **Vaughan** (T. Wayland). An addition to the coral fauna of the Aquia Eocene formation of Maryland.

Wash. Biol. Soc., Proc., vol. 15, pp. 205–206, 1902.

1242 —— A redescription of the coral Platytrochus speciosus.

Wash. Biol. Soc., Proc., vol. 15, pp. 207–209, 1902.

1243 —— Corrections to the nomenclature of the Eocene fossil corals of the United States.

Wash Biol. Soc., Proc., vol. 16, p. 101, 1903.

1244 —— The corals of the Buda limestone.

U. S. Geol. Surv., Bull. no. 205, pp. 37–40, pl. 27, 1903.

1245 —— Fuller's earth deposits of Florida and Georgia.

U. S. Geol. Surv. Bull. no. 213, pp. 392–399, 1903.

Describes geographic and geologic occurrence and character of deposits of fuller's earth in these States.

1246 —— See Arnold (Ralph), 38.

1247 **Veatch** (Arthur C.). The diversity of the Glacial period on Long Island.

Jour. Geol., vol. 11, pp. 762–776, figs. 1–6, 1903.

Discusses character, occurrence, geologic position, and correlation of glacial deposits on Gardiners and Long Islands, New York.

248 **Veatch** (Arthur C.). Notes on the geology of Long Island.
Science, new ser., vol. 18, pp. 213–214, 1903.
Discusses the occurrence of Quaternary formations and their relation to pre-Glacial topography.

249 **Villarello** (Juan D.). Genesis de los yacimientos mercuriales de Palomas y Huitzuco, en los estados de Durango y Guerrero de la Republica Mexicana.
Soc. Cien. Ant. Alz., Mem. y Rev., vol. 20, pp. 95–136, 1903.
Discusses origin of mercury-bearing ore deposits.

250 **Von Rosenberg** (Leo). Report on the properties of the Summit Coal Company, situated in Marshall County, State of West Virginia.
New York, 12 pp., 9 pls., 1903. (Privately printed.)
Contains geologic sections of Carboniferous strata and data bearing on coal production.

251 **Voyle** (Joseph). Aurite, and a general theory of gold ore genesis.
Mg. & Sci. Press, vol. 86, pp. 382–383, 1903.

W.

252 **Wagner** (George). Observations on Platygonus compressus Le Conte.
Jour. Geol., vol. 11, pp. 777–782, figs. 1–4, 1903.

253 **Walcott** (Charles D.). New term for the Upper Cambrian series.
Jour. Geol., vol. 11, pp. 318–319, 1903.
Proposes the term Saratogian for Upper Cambrian, and gives a list of formations referred to it.

254 —— John Wesley Powell.
Wash. Acad. Sci., Proc., vol. 5, pp. 99–130, pl. 1 (por.), 1903.

255 —— Twenty-fourth annual report of the Director of the United States Geological Survey to the Secretary of the Interior, 1902–3.
Washington, 302 pp., 26 pls., 1903.
Gives an account of the work of the U. S. Geological Survey for the year 1902–3. Includes a biographical sketch of J. W. Powell.
The rules governing the nomenclature and classification of geologic formations promulgated in the Tenth Annual Report, pp. 63–79, have been recently revised and, as revised, are given in this report on pp. 21–27.

256 **Waldo** (C. A.). Dikes in the Oklahoma Panhandle.
Abstract: Eng. & Mg. Jour., vol. 75, p. 153, 1903; Science, new ser., vol. 17, p. 220, 1903; Sci. Am. Suppl., vol. 55, p. 22647, 1903.

257 **Walker** (Bryant). On the shells of marls.
Mich. Geol. Surv., vol. 8, pt. 3, pp. 97–102, 1903.
Describes the occurrence of gastropodous shells in Michigan marl deposits.

1258 **Ward** (Henry A.). Catalogue of the Ward-Coonley collection of meteorites.

Chicago, 99 pp., 6 pls., 1900; 28 pp., 1901. (Private publication.)

Contains notes on the character and occurrence of meteorites.

1259 —— The Bath Furnace [Kentucky] meteorite.

Am. Jour. Sci., 4th ser., vol. 15, pp. 316–319, 1 fig., 1903.

Describes fall and characters.

1260 —— The Andover [Maine] meteorite.

Am. Jour. Sci., 4th ser., vol. 15, pp. 395–396, 1 fig., 1903.

1261 **Ward** (Lester F.). Correlation of the Potomac formation in Maryland and Virginia.

Abstract: Science, new ser., vol. 17, pp. 941–942, 1903.

1262 **Warman** (Philip Creveling). Catalogue and index of the publications of the United States Geological Survey, 1901 to 1903.

U. S. Geol. Surv., Bull. no. 215, 234 pp., 1903.

1263 —— Catalogue of the published writings of John Wesley Powell.

Wash. Acad. Sci., Proc., vol. 5, pp. 131–187, 1903.

1264 **Warren** (C. H.). Mineralogical notes. I. Native arsenic from Arizona. II. Anthophyllite with the fayalite from Rockport, Mass. III. Cerussite and phosgenite from Colorado.

Am. Jour. Sci., 4th ser., vol. 16, pp. 337–344, 1903.

Describes occurrence and characters of these minerals.

1265 **Washburne** (Chester). Notes on the marine sediments of eastern Oregon.

Jour. Geol., vol. 11, pp. 224–229, 1903.

Describes occurrence of fossiliferous limestone of Carboniferous age and gives notes on the occurrence of strata and fossils of Triassic, Jurassic, and Cretaceous age. Includes reports by George H. Girty on the fossils collected from the Carboniferous limestone and by T. W. Stanton on fossils from the Chico formation.

1266 **Washington** (Henry Stephens). Chemical analyses of igneous rocks published from 1884 to 1900, with a critical discussion of the character and use of analyses.

U. S. Geol. Surv., Professional Paper no. 14, 495 pp., 1903.

Discusses character of chemical analyses of igneous rocks, the construction and nomenclature of the new quantitative classification and its correlation with the qualitative system, and methods of calculation employed, and gives tables embracing nearly all published analyses of igneous rocks arranged according to the new system.

NOTE.—These chemical analyses have not been separately listed in the index.

1267 —— The calculation of center-points in the quantitative classification of igneous rocks.

Abstract: Science, new ser., vol. 17, p. 668, 1903.

1268 **Washington** (Henry Stephens). The quantitative distribution of rock magmas.

Abstract: Eng. & Mg. Jour., vol. 75, p. 153, 1903.

1269 —— and others. Quantitative classification of igneous rocks.

See Cross (Whitman) and others, 251.

1270 **Watson** (Thomas Leonard). Copper-bearing rocks of Virgilina copper district, Virginia and North Carolina.

Denison Univ., Sci. Lab., Bull., vol. 12, pp. 97–127, pls. 7–9, fig. 1, 1903.

Reviews previous work and describes the occurrence, petrographic characters, and composition of igneous rocks, and the occurrence and character of the deposits of copper ores.

1271 —— The yellow ocher deposits of the Cartersville district, Bartow County, Georgia.

Am. Inst. Mg. Engrs., Trans. (New York meeting, October, 1903), 24 pp.

Gives an account of the geology and topography of the district and describes the occurrence, composition and mining of the ocher deposits.

1272 —— Geological relations of the manganese ore deposits of Georgia.

Am. Inst. Mg. Engrs., Trans. (Albany meeting, February, 1903), 47 pp. Discussion, 3 pp.

Describes the stratigraphy and geologic structure and the character and occurrence of the manganese ores of the Paleozoic and crystalline rocks of northern Georgia and discusses the origin of the ore deposits.

1273 **Webster** (Arthur). Geology of the west coast of Vancouver Island.

Can. Geol. Surv., Summ. Rept. for 1902, pp. 52–74, 1903.

Describes observations upon the physical features, general geology, and economic resources of the region.

1274 **Weed** (Walter Harvey). Geological sketch of the Hot Springs district, Arkansas.

57th Cong., 1st Sess., Sen. Doc. no. 282, Washington, pp. 79–94, pls. 1–10, 1902.

Describes location, topography, and general geology of the region, and the source, character, and geologic relations of the hot springs, and discusses the origin of their heat.

1275 —— Gold mines of the Marysville district, Montana.

U. S. Geol. Surv., Bull. no. 213, pp. 88–89, 1903.

Gives a brief history of the development of the field, its geological features, and the occurrence of the ore bodies.

1276 —— Tin deposits at El Paso, Tex.

U. S. Geol. Surv., Bull. no. 213, pp. 99–102, 1903.

Describes briefly the geologic structure and formation of the Franklin Mountains, the character and occurrence of the ores, and the mining developments.

1277 **Weed** (Walter Harvey). Ore deposits at Butte, Mont.

U. S. Geol. Surv., Bull. no. 213, pp. 170–180, 1903.

Describes the mining development of the region, the character and occurrence of the rocks and structural features of the district, and the character, occurrence, and origin of the ore deposits and the vein systems.

1278 —— Copper deposits of the Appalachian States.

U. S. Geol. Surv., Bull. no. 213, pp. 181–185, 1903.

Describes the occurrence of deposits of copper ores in New Jersey, Maryland, Virginia, North Carolina, and Tennessee.

1279 —— Copper deposits of New Jersey.

N. J. Geol. Surv., Ann. Rept. for 1902, pp. 125–139, 1903.

Describes the occurrence, character, and structural conditions of the copper ores and the mining operations, and discusses the origin of the ores.

1280 —— Ore deposits near igneous contacts.

Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 715–746, fig. 1, 1903.

Gives a genetic classification of ore deposits, discusses formation of ores in contact zones, and especially the origin of contact metamorphic deposits.

1281 —— Ore deposition and vein enrichment by ascending hot waters.

Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 747–754, 1903.

1282 —— Secondary enrichment at Cripple Creek [Colorado].

Eng. & Mg. Jour., vol. 75, pp. 553–554, 1 fig., 1903.

1283 —— Cross vein ore shoots and fractures.

Eng. & Mg. Jour., vol. 76, p. 193, 1903.

Describes vein structure and discusses its origin.

1284 —— The Cananea ore deposits [Mexico].

Eng. & Mg. Jour., vol. 76, p. 383, 1903.

Gives observations upon the geology and the occurrence of the copper ore deposits.

1285 —— [Classification of ore deposits].

Abstract: Science, new ser., vol. 17, pp. 273–274, 1903.

1286 **Weeks** (Fred Boughton). Bibliography and index of North American geology, paleontology, petrology, and mineralogy for the year 1902.

U. S. Geol. Surv., Bull. no. 221, 200 pp., 1903.

1287 —— Tungsten ore in eastern Nevada. U. S. Geol. Surv., Bull. no. 213, p. 103, 1903.

Describes the character and occurrence of hübnerite in the Snake Mountains, Nevada.

1288 **Weeks** (Fred Boughton). Occurrence of Paleozoic rocks in the southern portion of the Great Basin region.

Abstract: Science, new ser., vol. 17, p. 26, 1903.

Describes briefly the occurrence and character of pre-Cambrian, Cambrian, Silurian, Devonian, and Carboniferous strata and the general geologic structure.

1289 **Weidman** (S.). The pre-Potsdam peneplain of the pre-Cambrian of north-central Wisconsin.

Jour. Geol., vol. 11, pp. 289–313, pl. 1, and text figs. 1–8, 1903.

Describes physiographic features and general structure of the peneplain, and discusses its formation, evidences as to its age, and its subsequent history.

1290 —— Note on the amphibole hudsonite previously called a pyroxene.

Am. Jour. Sci., 4th ser., vol. 15, pp. 227–232, 2 figs., 1903.

Describes microscopic and chemical characters.

1291 **Weller** (Stuart). The Paleozoic faunas [New Jersey].

N. J. Geol. Surv., Rept. on Paleont., vol. 3, 462 pp., 53 pls., 1903.

Describes the Paleozoic formations of New Jersey, gives lists of their included fossils and discusses the characteristics of the faunas and their correlation with those of other areas. Gives systematic descriptions and figures of the fossils of the several formations described.

1292 **Wells** (J. Walter). Molybdenite—its occurrence, concentration, and uses.

Can. Mg. Rev., vol. 22, pp. 113–118, figs. 1–4, 1903.

1293 **Wheelock** (C. E.). The Oriskany sandstone.

Onondaga Acad. Sci., Proc., vol. 1, pp. 39–44, 1903.

Describes distribution, character, and fossil contents of the Oriskany sandstone in Onondaga County, N. Y.

1294 **Whitaker** (Milton C.). An olivinite dike of the Magnolia district [Colorado] and the associated picrotitanite.

Colo. Sci. Soc., Proc., vol. 6, pp. 104–119 [1902].

Describes the occurrence, the megascopic and microscopic characters, and composition of olivinite, and the characters and composition of the associated picrotitanite.

1295 **White** (David). Memoir of Ralph Dupuy Lacoe.

Geol. Soc. Am., Bull., vol. 13, pp. 509–515, 1903.

Includes a list of publications.

1296 —— Summary of the fossil plants recorded from the upper Carboniferous and Permian formations of Kansas.

U. S. Geol. Surv., Bull. no. 211, pp. 85–117, 1903.

1297 —— Permian elements in the Dunkard flora.

Abstract: Science, new ser., vol. 17, p. 298, 1903.

1298 **White** (David). An anthracite coal field three and a half hours west of Washington.

Abstract: Science, new ser., vol. 17, p. 387, 1903.

Describes observations upon the geology and age of the Sleepy Creek Mountain coal basin of West Virginia.

1299 —— Age of the Mercer group.

Abstract: Science, new ser., vol. 17, p. 942, 1903.

1300 —— See Diller (J. S.), 302.

1301 **White** (I. C.). The Appalachian coal field [West Virginia].

W. Va. Geol. Surv., vol. 2, pp. 81–716, 1903.

Gives a detailed account of the Carboniferous system in West Virginia, including geologic sections, the extent, character, and geologic position of the various formations, and the character, occurrence, constitution, and fuel value of the coals.

1302 **Whiteaves** (J. F.). Description of a fossil Cyrena from Alberta.

Ottawa Nat., vol. 16, pp. 231–233, pl. 4, 1903.

1303 —— Crania of extinct bisons from the Klondike Creek gravels.

Ottawa Nat., vol. 16, pp. 240–241, 1903.

1304 —— Description of a new species of Matheria, from the Trenton limestone at Ottawa.

Ottawa Nat., vol. 17, pp. 32-34, fig. 1, 1903; Geol. Mag., new ser., dec. 4, vol. 10, pp. 358–359, fig. 1, 1903.

1305 —— Description of a species of Cardioceras from the Crows Nest coal fields.

Ottawa Nat., vol. 17, pp. 65–67, fig. 1, 1903.

1306 —— Notes on some Canadian specimens of "Lituites undatus."

Ottawa Nat., vol. 17, pp. 119–122, 1903.

Reviews literature bearing on the subject and discusses the generic placement and relationships of Canadian specimens.

1307 —— Additional notes on some Canadian specimens of "Lituites undatus."

Ottawa Nat., vol. 17, pp. 161–163, 1903.

1308 —— Mesozoic fossils. Part 5. On some additional fossils from the Vancouver Cretaceous, with a revised list of the species therefrom.

Can. Geol. Surv., Mesozoic Fossils, vol. 1, pp. 309–415, pls. 40–51, figs. 15–27, 1903.

1309 **Whitfield** (R. P.). Notice of six new species of Unios from the Laramie group.

Am. Mus. Nat. Hist., Bull., vol. 19, pp. 483-487, pls. 38–40, 1903.

1310 —— Observations on a remarkable specimen of Halysites and description of a new species of the genus.

Am. Mus. Nat. Hist., Bull., vol. 19, pp. 489–490, pls. 41–42, 1903.

1311 **Whitlock** (H. P.). List of New York mineral localities.

N. Y. State Mus., Bull. 70, 108 pp., 1903.

Tabulates the occurrence and geologic association of minerals found in the State of New York.

1312 **Whittemore** (Charles A.). The sub-Carboniferous limestone exposure at Grand Rapids, Mich.

Mich. Acad. Sci., 1st Rept., pp. 62-65, 1900.

Describes the occurrence and character, and notes the fossils occurring therein.

1313 **Wieland** (G. R.) Notes on the marine turtle Archelon: 1, on the structure of the carapace; 2, associated fossils.

Am. Jour. Sci., 4th ser., vol. 15, pp. 211-216, 1 fig., 1903.

Describes the rib series of Archelon ischyros from new material.

1314 —— Polar climate in time the major factor in the evolution of plants and animals.

Am. Jour. Sci., 4th ser., vol. 16, pp. 401-430, 1903.

1315 —— Extent and progress of cycad investigation.

Science, new ser., vol. 17, pp. 352-353, 1903.

1316 **Wilder** (Frank A.). The age and origin of the gypsum of central Iowa.

Jour. Geol., vol. 11, pp. 723-748, figs. 1-3, 1903.

Describes occurrence, character, and geologic position of the gypsum deposits, and discusses their age and mode of formation.

1317 —— Possible origin for the lignites of North Dakota.

Iowa Acad. Sci., Proc. for 1902, vol. 10, pp. 129-135, 1903.

Describes occurrence and characters of lignite beds in North Dakota and Montana and offers an explanation of their origin.

1318 **Wilder** (Henry J.), **Burke** (R. T. A.) and. Soil survey of the Trenton area, New Jersey.

See Burke (R. T. A.) and Wilder (H. J.), 144.

1319 **Williams** (E. G.). The manganese industry of the Department of Panama, Republic of Colombia.

Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 197-234, figs. 1-9, 1903.

Discusses the character and occurrence of the manganese ore deposits and the mining operations.

1320 **Williams** (Henry Shaler). Shifting of faunas as a problem of stratigraphic geology.

Geol. Soc. Am., Bull., vol. 14, pp. 177-190, pl. 16, 1903.

Discusses relationships of faunas in different types of sediments in the Devonian of New York, Pennsylvania, and Ohio and their shifting, and gives rules for the use of fossils in stratigraphy.

1321 **Williams** (Henry Shaler). The correlation of geological faunas, a contribution to Devonian paleontology.

U. S. Geol. Surv., Bull. no. 210, 147 pp., 1903.

Discusses faunas of upper Devonian, with especial reference to the statistics of the species, the evidences for the shiftings of faunas and the consequences thereof, and the value and use of fossils in correlation work.

1322 **Willis** (Bailey). Physiography and deformation of the Wenatchee-Chelan District, Cascade Range [Washington].

U. S. Geol. Surv., Professional Paper no. 19, pp. 41–97, pls. 8–20, figs. 2–3, 1903.

Describes physiographic features of the region and their history.

1323 —— Ames Knob, North Haven, Maine.

Geol. Soc. Am., Bull., vol. 13, pp. 201–206, pls. 17–18, 1903; Am. Geol., vol. 31, p. 159, 1903.

Describes physiographic and glacial evidences showing submergence and re-elevation.

1324 —— Post-Tertiary deformation of the Cascade Range.

Abstract: Science, new ser., vol. 17, p. 740, 1903.

1325 **Williston** (Samuel W.). North American plesiosaurs. Part I.

Field Col. Mus., Geol. Ser., vol. 2, pp. 1–77, pls. 1–29, figs. 1–13, 1903.

1326 —— On the osteology of Nyctosaurus (Nyctodactylus), with notes on American pterosaurs.

Field Col. Mus., Geol. Ser., vol. 2, pp. 25–163, pls. 40–44, figs. 1–2, 1903.

1327 —— On the structure of the plesiosaurian skull.

Science, new ser., vol. 17, p. 980, 1903.

1328 —— Some osteological terms.

Science, new ser., vol. 18, pp. 829–830, 1903.

1329 —— The fossil man of Lansing, Kansas.

Pop. Sci. Monthly, vol. 62, pp. 463–473, ill., 1903.

Describes the occurrence of the human remains and discusses the evidences of their age.

1330 —— Cretaceous fishes, Selachians and Pycnodonts.

Kans. Univ. Geol. Surv., vol. 6, pp. 237–256, pls. 23–32, 1900.

1331 —— See Winchell (N. H.), 1342.

1332 **Wilson** (Alfred W. G.). The Laurentian peneplain.

Jour. Geol., vol. 11, pp. 615–669, figs. 1–14, 1903; McGill Univ., Papers from Dept. Geol., no. 15, 1903.

Describes location, physiographic control, topographic and drainage features, and discusses the origin of the Laurentian peneplain and some of its features.

1333 **Wilson** (Alfred W. G.). A geological reconnoissance about the headwaters of the Albany River [Canada].

Can. Geol. Surv., Summ. Rept. for 1902, pp. 201–206, 1903.

Gives observations upon the topography and geology of the region examined.

1334 —— The theory of the formation of sedimentary deposits.

Can. Rec. Sci., vol. 9, pp. 112–132, figs. 1–4, 1903; McGill Univ., Papers from the Dept. Geol., no. 16, 1904.

Discusses the conditions and processes of sedimentation and their bearing upon the character and correlation of some Ordovician and Silurian formations of Canada.

1335 **Wilson** (John D.). Fauna of the Agoniatite limestone of Onondaga County, N. Y.

Onondaga Acad. Sci., Proc., vol. 1, pp. 84–88, 1903.

Describes the occurrence, character, and fossils of the Agoniatite limestone of the Marcellus shale in Onondaga County, N. Y.

1336 **Wilson** (W. J.). Reconnoissance surveys of Four Rivers southwest of James Bay.

Can. Geol. Surv., Summ. Rept. for 1902, pp. 220–239, 1903.

Contains observations upon the geology of the region examined.

1337 **Winchell** (Alexander N.). Note on titaniferous pyroxene.

Am. Geol., vol. 31, pp. 309–310, 1903.

Discusses composition and optic angle.

1338 —— [In discussion of paper by J. E. Spurr, "A consideration of igneous rocks and their segregation or differentiation as related to the occurrence of ores."]

Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 1063–1064, 1903.

Discusses an example of ore concentration in Madison County, Montana.

1339 **Winchell** (Horace V.). Synthesis of chalcocite and its genesis at Butte, Montana.

Geol. Soc. Am., Bull., vol. 14, pp. 269–276, 1903; Eng. & Mg. Jour., vol. 75, pp. 782–784, 1903.

Discusses occurrence and experiments to determine origin of chalcopyrite.

1340 —— The Mesabi iron range [Minnesota].

Eng. & Mg. Jour., vol. 76, pp. 343–344, 1903.

Discusses geologic work upon the Mesabi iron range.

1341 **Winchell** (Newton H.). Some results of the late Minnesota Geological Survey.

Am. Geol., vol. 31, pp. 246–253, 1903.

Gives a brief summary of the results of this survey.

1342 **Winchell** (Newton H.) The Pleistocene geology of the Concannon farm, near Lansing, Kansas.

Am. Geol., vol. 31, pp. 263–308, pls. 15–18, 1903.

Summarizes and discusses Professor Chamberlain's paper on "The geologic relations of the human relics of Lansing, Kansas" (Jour. Geol., vol. 10, pp. 745–779, 1902), describes the general geologic relations and character of the deposits where the human remains were found, and discusses their age and mode of formation. Includes contributions by S. W. Williston, J. E. Todd, and G. Frederick Wright.

1343 —— Regeneration of clastic feldspar.

Geol. Soc. Am., Bull., vol. 13, pp. 522–525, 1903.

Reviews previous literature on the subject and discusses three phases of the changes through which feldspars pass.

1344 —— Was man in America in the Glacial period?

Geol. Soc. Am., Bull., vol. 14, pp. 133–152, fig. 1, 1903.

Describes conditions prevailing in North America during Tertiary times, discusses character of the pre-Glacial geest covering, the advent of the ice sheets, origin of the loess, and the occurrence and character of the Lansing skeleton.

1345 —— Metamorphism of the Laurentian limestones of Canada.

Am. Geol., vol. 32, pp. 385–392, 1903.

A review of a paper by Louis Caryl Graton "On the petrographical relations of the Laurentian limestones and the granite in the township of Glamorgan, Haliburton County, Ontario" (Can. Rec. Sci., vol. 9, pp. 1–38, 1903).

1346 —— Granite. Address at unveiling of the Coronado obelisk at Logan Grove, Kansas, Aug. 12, 1902.

Memoirs of Exploration in the Basin of the Mississippi, vol. 7, Kansas, pp. 87–91, 1903.

Includes a discussion of Archean geologic history and the origin of granite.

1347 **Winterton** (J.). The volcanic eruptions in Guatemala.

Sc. Am., vol. 89, p. 84, ill., 1903.

1348 **Wolff** (J. E.). Zinc and manganese deposits of Franklin Furnace, N. J.

U. S. Geol. Surv., Bull. no. 213, pp. 214–217, 1903.

Describes the character, geologic occurrence, and origin of the zinc deposits.

1349 **Woodward** (H.). Note on some fragmentary remains of fossils from the upper part of Mount Noyes (Canadian Rockies).

Geol. Mag., new ser., dec. 4, vol. 10, pp. 297–298, figs. 1–3, 1903.

1350 **Woodward** (R. S.) and others. Report of advisory committee on geophysics.

Carnegie Inst. Wash., Yearbook no. 1, 1902, pp. 26–70, 1903.

Discusses problems of geophysics and methods of investigation.

1351 **Woodworth** (Jay B.). On the sedentary impression of the animal whose trail is known as Climactichnites.

N. Y. State Mus., Bull. 69, pp. 959–966, pls. A–B, figs. 1–3, 1903.

Describes occurrence and character of the trails known as Climactichnites and discusses their formation.

1352 —— The Northumberland volcanic plug.

N. Y. State Mus., 55th Ann. Rept., pp. r17–r24, pls. 2–6, figs. 1–3, 1903.

Describes the occurrence, character and geologic relations of an igneous rock mass discovered near Schuylerville, New York, to which the name Stark's Knob is given.

1353 —— Note on the elevated beaches of Cape Ann, Mass.

Harvard Coll., Mus. Comp. Zool., Bull., vol. 42, pp. 191–194, 1903.

1354 **Woolman** (Lewis). Report on artesian wells [New Jersey].

N. J. Geol. Surv., Ann. Rept. for 1902, pp. 61–95, 1903.

1355 **Wortman** (J. L.). Studies of Eocene mammalia in the Marsh collection, Peabody Museum. Part II, Primates.

Am. Jour. Sci., 4th ser., vol. 15, pp. 163–176, figs. 100–104; pp. 399-414, 419–436; vol. 16, pp. 345–368, figs. 105–119, pls. 16–17, 1903.

Discusses characters, relationships, classification, origin, and distribution of primates and gives descriptions of forms belonging to the Cheiromyidæ.

1356 **Wright** (Frederick Bennett). The mastodon and mammoth contemporary with man.

Records of the Past, vol. 2, pp. 243–253, ill., 1903.

1357 **Wright** (George Frederick). The age of the Lansing skeleton.

Records of the Past, vol. 2, pp. 119–124, ill., 1903.

1358 —— Glacial man.

Records of the Past, vol. 2, pp. 259–271, ill., 1903.

1359 —— The Lansing skull and the early history of mankind.

Bibliotheca Sacra, 73d yr., pp. 28–32, 1903.

1360 —— The revision of geological time.

Bibliotheca Sacra, 73d yr., pp. 578–582, 1903.

Reviews and discusses the evidence for the length of post-Glacial time.

1361 —— The problem of the loess in the Missouri Valley compared with that in Europe and Asia.

Abstract: Science, new ser., vol. 17, pp. 227–228, 1903; Sci. Am. Suppl., vol. 55, p. 22666, 1903.

1362 —— See Winchell (N. H.), 1342.

1363 **Wuensch** (A. F.). The Arizpe meteorite [Mexico].

Colo. Sci. Soc., Proc., vol. 7, pp. 67–68, ill., 1903.

Y.

1364 **Yates** (J. A.). The Ottawa [Kansas] gas wells.

Kans. Acad. Sci., Trans., vol. 18, pp. 106–108, 1903.

Describes the exploration for natural gas and gives a record of the borings.

1365 **Yates** (Lorenzo Gordin). Prehistoric California.

So. Cal. Acad. Sci., Bull., vol. 1, pp. 81–86, 3 pls.; pp. 97–100, pls. 4–7; pp. 113–118, pls. 1–2; pp. 129–137, pls. 3–4, 1902; vol. 2, pp. 145–155, 2 pls.; pp. 17–22, figs. 1–3; pp. 44–51, pls. 1–4; pp. 74–75, pl. 5; pp. 87–93, pls. 6–8; pp. 97–101, pls. 9–10; pp. 113–118, pls. 11–12, 1903.

Describes physiography and general geologic structure and history of southern California, and the character of the flora and fauna during Tertiary time, and gives lists and figures of and notes upon fossil plants and animals.

1366 **Young** (L. E.), **Beyer** (S. W.) and. Geology of Monroe County, Iowa.

See Beyer (S. W.) and Young (L. E.), 78.

1367 **Yung** (Morrison B.) and **McCaffery** (Richard S.). The ore deposits of the San Pedro district, New Mexico.

Am. Inst. Mg. Engrs., Trans., vol. 33, pp. 350–362, figs. 1–7, 1903; Eng. & Mg. Jour., vol. 75, pp. 297–299, figs. 1–4, 1903.

Describes the general geology of the region, and the occurrences, geologic relations, and character of the copper, silver-lead, and gold deposits.

ADDENDA TO BIBLIOGRAPHIES FOR PREVIOUS YEARS.

1894	**1895**	**1896**	**1897**	**1898**
1077	391	299	220	74
			221	222
			300	329
			1078	782
				914

1899	**1900**			
419	1	429	628	872
922	64	432	808	923
1079	310	497	869	1120
	324	624	870	1130

1901	**1902**			
81	20	356	672	858
82	21	402	692	874
95	42	416	699	911
102	43	453	711	915
103	50	468	712	916
104	71	497	713	941
227	79	500	714	942
234	86	504	715	943
242	105	518	716	961
311	106	534	717	962
312	107	541	718	966
313	114	561	719	967
321	122	575	727	977
322	142	584	754	1008
330	143	590	755	1113
331	149	591	760	1142
342	150	596	769	1143
382	157	599	772	1184
433	177	616	773	1202
434	215	640	774	1204
462	216	641	841	1235
497	224	650	846	1239
503	234	657	847	1241
578	269	658	854	1242
595	293	669	855	1274
652	306	670	856	1294
750	314	671	857	1365
791				
871				
873				
902				
1007				
1053				
1141				
1225				

CLASSIFIED KEY TO THE INDEX.

INDEX.

[The numbers refer to entries in the Bibliography.]

[a] The chemical analyses appearing in Washington's "Chemical Analyses of Igneous Rocks, published from 1884 to 1900," have not been listed.

Geologic formations described—Continued.

Geologic formations described—Continued.

Geologic formations described—Continued.

Geologic formations described—Continued.

[a] Includes geologic maps of the whole or any part of the States mentioned.

O

PUBLICATIONS OF UNITED STATES GEOLOGICAL SURVEY.

[Bulletin No. 240.]

The serial publications of the United States Geological Survey consist of (1) Annual Reports, (2) Monographs, (3) Professional Papers, (4) Bulletins, (5) Mineral Resources, (6) Water-Supply and Irrigation Papers, (7) Topographic Atlas of United States—folios and separate sheets thereof, (8) Geologic Atlas of United States—folios thereof. The classes numbered 2, 7, and 8 are sold at cost of publication; the others are distributed free. A circular giving complete lists may be had on application.

The Professional Papers, Bulletins, and Water-Supply Papers treat of a variety of subjects, and the total number issued is large. They have therefore been classified into the following series: A, Economic geology; B, Descriptive geology; C, Systematic geology and paleontology; D, Petrography and mineralogy; E, Chemistry and physics; F, Geography; G, Miscellaneous; H, Forestry; I, Irrigation; J, Water storage; K, Pumping water; L, Quality of water; M, General hydrographic investigations; N, Water power; O, Underground waters; P, Hydrographic progress reports. This bulletin is the twenty-eighth in Series G, the complete list of which follows (all are bulletins thus far):

BULLETINS, SERIES G, MISCELLANEOUS.

2. Gold and silver conversion tables, giving the coining values of troy ounces of fine metal, etc., computed by Albert Williams, jr. 1883. 8 pp.
7. Mapoteca geologica Americana: A catalogue of geological maps of America (North and South), 1752–1881, in geographic and chronologic order, by Jules Marcou and John Belknap Marcou. 1884. 184 pp.
25. The present technical condition of the steel industry of the United States, by Phineas Barnes. 1885. 85 pp.
26. Copper smelting, by Henry M. Howe. 1885. 107 pp.
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75. Record of North American geology for 1887–1889, inclusive, by Nelson Horatio Darton. 1891. 173 pp.
91. Record of North American geology for 1890, by Nelson Horatio Darton. 1891. 88 pp.
99. Record of North American geology for 1891, by Nelson Horatio Darton. 1892. 73 pp.
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140. Report of progress of the division of hydrography for the calendar year 1895, by Frederick Haynes Newell. 1896. 356 pp.
146. Bibliography and index of North American geology, paleontology, petrology, and mineralogy for the year 1895, by Fred Boughton Weeks. 1896. 130 pp.
149. Bibliography and index of North American geology, paleontology, petrology, and mineralogy for the year 1896, by Fred Boughton Weeks. 1897. 152 pp.
156. Bibliography and index of North American geology, paleontology, petrology, and mineralogy for the year 1897, by Fred Boughton Weeks. 1898. 130 pp.
162. Bibliography and index of North American geology, paleontology, petrology, and mineralogy for the year 1898, by Fred Boughton Weeks. 1899. 163 pp.
172. Bibliography and index of North American geology, paleontology, petrology, and mineralogy for the year 1899, by Fred Boughton Weeks. 1900. 141 pp.
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188. Bibliography of North American geology, paleontology, petrology, and mineralogy for the years 1892–1900, inclusive, by Fred Boughton Weeks. 1902. 717 pp.
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215. Catalogue and index of the publications of the United States Geological Survey, 1901 to 1903, by Philip Creveling Warman. 1903. 234 pp.
221. Bibliography and index of North American geology, paleontology, petrology, and mineralogy for the year 1902, by Fred Boughton Weeks. 1903. 200 pp.
222. Catalogue and index of the publications of the Hayden, King, Powell, and Wheeler surveys, by L. F. Schmeckebier. 1904. 208 pp.
227. The United States Geological Survey, its origin, development, organization, and operations. 1904. 205 pp.
240. Bibliography and index of North American geology, paleontology, petrology, and mineralogy for the year 1903, by Fred Boughton Weeks. 1904. 243 pp.

Correspondence should be addressed to

The Director,
United States Geological Survey,
Washington, D. C.

October, 1904.

[Mount each slip upon a separate card, placing the subject at the top of the second slip. The name of the series should not be repeated on the series card, but the additional numbers should be added, as received, to the first entry.]

Author.

Weeks, Fred Boughton.

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243, III p. $23\frac{1}{2}^{cm}$. (U. S. Geological survey. Bulletin no. 240.)
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Reference.

U. S. Dept. of the Interior.

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DEPARTMENT OF THE INTERIOR

UNITED STATES GEOLOGICAL SURVEY

CHARLES D. WALCOTT, DIRECTOR

EXPERIMENTS

ON

SCHISTOSITY AND SLATY CLEAVAGE

BY

GEORGE F. BECKER

WASHINGTON
GOVERNMENT PRINTING OFFICE
1904

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LETTER OF TRANSMITTAL.

Department of the Interior,
United States Geological Survey,
Washington, D. C., June 4, 1904.

Sir: I have the honor to transmit herewith a paper by myself describing experiments made for the purpose of testing disputed theories of schistosity and slaty cleavage.

Very respectfully,

George F. Becker,
Geologist in Charge Division of Chemical and Physical Research.

Hon. Charles D. Walcott,
Director United States Geological Survey.

EXPERIMENTS ON SCHISTOSITY AND SLATY CLEAVAGE.

By George F. Becker.

Abundance of fissile rocks.—A very large part of the rocks exposed at the earth's surface exhibit schistosity or cleavability not ascribable to sedimentation and often well marked in masses of igneous origin. In many cases the surfaces along which rocks cleave intersect one another, producing a foliated structure. In other instances the cleavage occurs in nearly parallel planes or along surfaces having large radii of curvature. None of these phenomena are confined to highly indurated rocks, as might be inferred from some discussions, but are found well developed in soft and fragile unmetamorphosed shales, as all who have made observations in disturbed Tertiary areas are aware. Specimens of these shales are so fragile, however, that they are scantily represented in collections. Slaty cleavage, as the term is used in this paper, means simply the most regular and extreme form of cleavability or schistosity, in which the laminæ are thin and are bounded by substantially parallel surfaces, no matter whether the material exhibiting these properties is indurated, as in the valuable roofing slates, or is soft and fragile, as in the comparatively worthless shales. Though argillaceous rocks exhibit the most perfect cleavage, this does not apparently differ in kind from the schistosity sometimes found in grit beds, limestone, granite, quartzite, and basic eruptives. A structure which is at least analogous is found in rolled or drawn metals, in terra-cotta articles, such as roofing tiles, and in pastry.[a] In short, slaty cleavage is a structure, or a group of structures not readily distinguishable from one another, and has a character of its own independent of the material which may exhibit it, although some substances are better fitted than others to display it in perfection. This relationship is recognized in the French term "schiste," which, in Gallic usage, comprehends shales, slates, and the crystalline schists of English writers. In English usage schist is commonly synonymous with crystalline schist, but the frequent use of this adjective would seem to imply the existence of schists which are not crystalline, and these could hardly be defined otherwise than as equivalent to shales.

[a] Cf. Daubrée, A., Géol. Exp., pp. 398 and 428.

Slaty cleavage, even in highly indurated rock, passes over by insensible gradations into less simple forms of schistosity, and vast masses of the crystalline schists show cleavage planes in systems intersecting one another at acute angles. It has always seemed to me that a true explanation of cleavage must include the theory of foliated schists as well as of roofing slate. The association of mica with cleavable rocks has often been insisted upon, perhaps with too great emphasis. Some shales contain much mica, but others contain only a little. According to Professor Rosenbusch, shales (Schieferthone) have the same mineralogical composition as clays, and mica is not an essential constituent. Sorby mentions clay slates which carry very little mica, and G. W. Hawes[a] describes a roofing slate from Littleton, N. H., which on microscopic examination is found to consist of fragments of quartz and feldspar as fine as dust, although in the larger part of the rocks called clay slate in New Hampshire he found abundant mica. Now clay slates and some shales have as good cleavage as mica-schists. Again, quartz-schists and other cleavable rocks contain very little mica. The grit beds or sandy strata found in slates do not always contain much mica, and yet their cleavage is manifestly of the same origin as that of the slate in which they are embedded. It is well known that near intrusive masses mica-schist not infrequently passes over into ordinary schists, and these into phyllites and clay slates, as if the amount of mica were characteristic of the degree of metamorphism rather than an index of the cleavability. "Compression," says Sir Archibald Geikie, "may give rise to slaty cleavage. But it has often been accompanied or followed by further internal transformations in the rocks. Chemical reactions have been set up and new minerals have been formed." In the study of slates it is often manifest that a portion of the mica is secondary. Thus on blind joints (Ausweichungsclivage of Heim) large continuous sheets of mica are frequently found. Muscovite is also well known to be one of the chief decomposition products of the feldspars, an alteration which is readily intelligible from a chemical standpoint. The increase of the mica content of phyllites as compared with shales seems to me most reasonably accounted for as a concomitant of the genesis of cleavage, though not an essential one.

Importance of cleavage.—Schistosity as a structure is important, and it is a part of the business of geologists to explain its origin. Slaty cleavage has further and greater importance as a possible tectonic feature. Scarcely a great mountain range exists, or has existed, along the course of which belts of slaty rock are not found, the dip of the cleavage usually approaching verticality. Are these slate belts equivalent to minutely distributed step faults of great total throw, or do they indicate compression perpendicular to the cleavage without attendant

[a] Hitchcock, C. H., Geology of New Hampshire, vol. 3, 1878, pt. 4, pp. 237, 238.

relative dislocation? Evidently the answer to this question is of first importance in the interpretation of orogenic phenomena.

Theories of cleavage.—The earliest theory of slaty cleavage assimilated it to mineral cleavage, a view not tenable after microscopic study. Mr. John Phillips in 1843 was the first to interpret slaty cleavage as an effect of mechanical strain. Mr. Daniel Sharpe in 1849 offered the explanation now most generally accepted by geologists, viz, that a fracture perpendicular to the line of pressure would run along the flattest faces of the component grains and meet the smallest number of them—a theory implying that the mass is heterogeneous and that the adhesion between the component particles is smaller than the cohesion within the particles. Dr. H. C. Sorby later described a variety of cleavage due to the presence of numerous microscopic blind joints.[a] Professor Tyndall in 1856 made exceedingly interesting experiments on this subject, obtaining admirable cleavage in wax. He denied that heterogeneity aided cleavage. In his first paper he asserted most emphatically that the cleavage was perpendicular to the direction of pressure, but in a footnote and in a later paper he indicated decided doubt as to this perpendicularity. Professor Daubrée (1879) also dissented from the view that heterogeneity is essential to slaty cleavage, and ascribed this structure to gliding ("glissement," slide) in the mass, which is equivalent to a denial of the perpendicularity of the causative force to the consequent cleavage.[b] In 1893 I published a theory founded on experiment and analysis. It is in agreement with Daubrée's idea, but more precise. According to this theory, cleavage is due to a weakening of cohesion[c] along planes of maximum tangential strain (or maximum slide). It is susceptible of proof[d] that deformation due to pressure is actually effected by relative motion of the mass in opposite directions parallel to these planes. When this movement exceeds the elastic limit and falls short of the breaking strain, it would seem inevi-

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[a] Sorby's theory of slate was that the preliminary effect of pressure on argillaceous strata is to give the mica an irregular distribution, and the final effect to rearrange the mica in new parallel planes. This hypothesis is still accepted in some text-books. To me it appears too fanciful for serious discussion. If mica scales, in all possible orientations, were to be mingled with mud, their average inclination to any plane would be 32° 42′ (or the well-known "average latitude of all places north of the equator"). If such a mass were to be compressed until the average angle were only 2° to a given plane, the thickness of the mass must be reduced to one-eighteenth. If a sediment containing mica were to be treated according to Sorby's theory, it would seemingly be needful to press it at first in such a way as to increase its thickness some eighteen times and then to compress it again in another direction to about its original thickness.

The attempt has been made to account for the cleavage surfaces on Sorby's hypothesis as maximum cleavability. I can not concur in this view. The cleavage in slate is confined within very narrow limits, perhaps one degree. Slate may be broken indeed at greater inclinations, but the ruptured surfaces do not then show imperfect cleavage; they are conchoidal or irregular and destitute of cleavage.

[b] The reader will find a digest of the literature in Mr. Alfred Harker's memoir on slaty cleavage, Brit. Assoc., 1885, p. 813, and some further notes in my paper on finite homogeneous strain, flow, and rupture of rocks, Bull. Geol. Soc. America, vol. 4, 1893, pp. 75–87.

[c] As H. Rogers put it, "the cohesive force is obviously at a minimum of intensity in the direction perpendicular to these planes" of cleavage. Trans. Royal Soc., Edinburgh, vol. 21, 1857, p. 450.

[d] See note on the theory of slaty cleavage appended to this paper.

table that the cohesion should be diminished and that cleavage should result.[a] Only in ideally brittle substances is there no interval between the elastic limit and the breaking strain. It is of course certain that the material constituting slate has been strained far beyond its elastic limit; and that it has a breaking strain is often manifested by blind joints. These planes stand at an angle of 45° or more to the direction of greatest local linear compression. There are at least two sets of them, and maybe four, symmetrically disposed with reference to this direction. In cases of double cleavage—so usual in disturbed areas, both in distinct development and in the more or less irregular form of ordinary schistosity and foliation—cleavage is produced on both sets of planes, so that a cross section shows acute-angled rhombs somewhat like those indicated in fig. 13, Pl. III, and in fig. 30, Pl. VI. In the case of forces acting on a supported mass at an acute angle to the plane of support, it was shown in my paper that the effect of viscosity would be to suppress all but one set of cleavages and to accentuate this remaining one. Tyndall's experiment, properly considered, was shown to be a case of this kind, and it was maintained that the cleavage of roofing slate is thus to be explained. If this be true, a belt of slate is equivalent to a great fault distributed over an infinite number of infinitesimal steps.[b]

Distinction between Sharpe's theory and mine.—The distinction between Sharpe's theory and mine is well defined. If in any portion of the mass before strain a small sphere is supposed to be marked out, this sphere after strain will have become an ellipsoid, called the strain ellipsoid. If Sharpe's theory is correct, the cleavage due to pressure will be in surfaces perpendicular to the smallest axis of the strain ellipsoid. If my theory is correct, the cleavage will make with this smallest axis an acute angle equal to or greater than 45°, and increasing as the strain grows greater.

Means of studying the strain ellipsoid.—The general nature of the experiments needed to compare the theories is made plain by this contrast. It amounts to a study of the strain ellipsoid. One means to this end is to incorporate into a mass to be experimented upon small spheres of the same material as the remainder, but of a distinguishable color. After straining is effected dissection or rupture, by exposing the distorted sphere, will show the local character of the strain and the posi-

[a] A pertinent illustration of weakening of cohesion is afforded by bars of mild steel ruptured by tension. The most plausible a priori idea of rupture by tension is that it would occur in a plane perpendicular to the line of force; and in hard steels this mode of rupture is often observed. In mild steels, on the other hand, the surface of rupture is rough and granular, the grains approaching pyramidal forms. The aggregate surface of such a fracture is far in excess of that of the mean plane. Now, since the rupture must follow a surface of least resistance, the resistance per unit area on the pyramidal faces must have been much smaller than that on the plane surface perpendicular to the tension. This can be due only to a weakening of cohesion along the pyramidal faces.

[b] This theory embraces rupture as well as simple and double or multiple cleavage. So far as jointing and cleavage due to blind joints are concerned, it has been accepted by some geologists, who regard true cleavage as a distinct phenomenon.

tions of the axes of the strain ellipsoid. Numerous experiments of this description have been made for this paper, and some of them are illustrated in fig. 2, Pl. II. They are instructive, but not sufficiently so. If it were practicable to build up an adequate block of small spheres and to fill in the interstices uniformly with the same material differently colored, the mass after strain would show the character of the strain ellipsoid at uniformly spaced intervals. This is impracticable, but the result sought can be attained very approximately in another way. If a block of material be pierced with fine holes at regular intervals, forming in one plane a network of small squares such as is shown in fig. 5, Pl. II, and the holes be filled with coloring matter, then strain, followed by dissection, will show the figures into which the small squares have been distorted. If the squares were very small, the sides of the distorted figures would be nearly straight and parallel. It would then be easy by a geometrical construction to inscribe ellipses tangent to the four sides at their middle points, and these ellipses would accurately represent the section of the strain ellipsoid. Even if the sides were somewhat curved, the strain at the center of the curvilinear parallelogram would be very closely represented by an ellipse found by a rational system of interpolation, as will be described in a note appended to this paper. Experiments have been made in this way also, the distorted figures being photographed and photographically enlarged to a convenient scale for constructing the ellipses.

Linear compression.—Experiments by Tyndall's method are very simply and easily executed, but the resulting strain is highly complex and indeed could not be discussed as a problem of pure mechanics in the present state of knowledge of the transmission of energy in plastic bodies. By the means noted in the last paragraph such experiments can be sufficiently elucidated for an investigation of slaty cleavage.

Rolling.—Another known means of producing slaty cleavage is by rolling out a cake of suitable material as a cook prepares pastry, or by passing the mass between rolls. It is easy to prick holes perpendicular to the surface of the cake before rolling, fill them with pigment, and, after distortion, to dissect the mass. The nature of the effect is seen in fig. 4 of Pl. II, the originally vertical lines being drawn out into parabola-like curves which are vertical only at the apex. Cleavage may be developed especially near the upper and lower surfaces of the rolled mass, to which it is nearly parallel. Such experiments, however, give results which are less definite and less easily discussed than those given by Tyndall's method. The manner of applying the force and the degree of rolling affect the result, as a matter of course, and it seems difficult to establish a standard of conditions.

Scission engine.—It is evidently most desirable to make experiments by producing simple well-known strains which will or may lead to cleavage. For this purpose I designed what may be called a "scission engine," a simple mechanism, shown without its cover in fig. 1, Pl. I. A block of material to be experimented upon is placed in the space B, the cover (provided with grooves to receive PP) is put on, screwed down onto pillars, and the driving screw set in motion. The bars F H revolve round the fixed pivots F, and the hinges H bend while the plates PP slide in their own planes. The area and volume of the space B remain constant and the strain produced is approximately a scission (or shearing motion). On four of the six faces, however, there is friction, which interferes somewhat, but not seriously, with the perfection of the strain.[a] If a circle is inscribed on the upper surface of the block before strain, it becomes approximately an ellipse showing the orientation of the strain ellipsoid. When the space B is thoroughly filled, no rupture within the mass is possible, the finite movement being distributed over an infinite number of planes; but if the space is not filled, complex strains result and rupture may occur. The engine gives about the unit strain, or produces a block with two angles of 45°.

Ceresin and its treatment.—The experiments to be described have been made principally with ceresin and a smooth clay such as is used by sculptors for modeling. I have tried white wax, which was the material employed by Tyndall, but white ceresin is preferable. This substance is refined ozocerite and consists of a mixture of paraffins. The material at my disposal melts at about 60° C., but some of the component paraffins solidify at a higher temperature, so that at 60° the cooling melt is a pasty mass, like thick oatmeal gruel. It contracts greatly in solidifying and should be cast at as low a temperature as practicable to prevent radial crystallization. Shavings of the solidified mass under the microscope show brilliant polarization colors, so that the mass is a crystalline solid. A particle fused on a slide and allowed to cool also shows high double refraction and exhibits a hypidiomorphic structure, analogous to that of semiporphyritic granites of excessively fine grain. Castings chilled in ice and salt and then broken with a hammer display a very fine-grained granular structure and somewhat conchoidal fracture, with no apparent radial crystallization.

The strong analogy between this solid and a rock is deserving of special emphasis. I can not see how deformations in masses of ceresin can possibly differ in character from those in the vastly less tractable crystalline rocks.

In carrying out Tyndall's experiment with ceresin I cast cylinders about $1\frac{1}{2}$ inches in diameter and nearly 2 inches in length. After the cylinders were cold the ends were planed down until all trace of the pit due to contraction was removed. Before compressing them they remained in a thermostat for some hours at 35°, because at considerably lower temperatures they rupture or crumble too easily. Com-

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[a] To obviate in some measure the effect of friction toward the center of the block, I made the space B 6 cm. long and only 4 cm. wide.

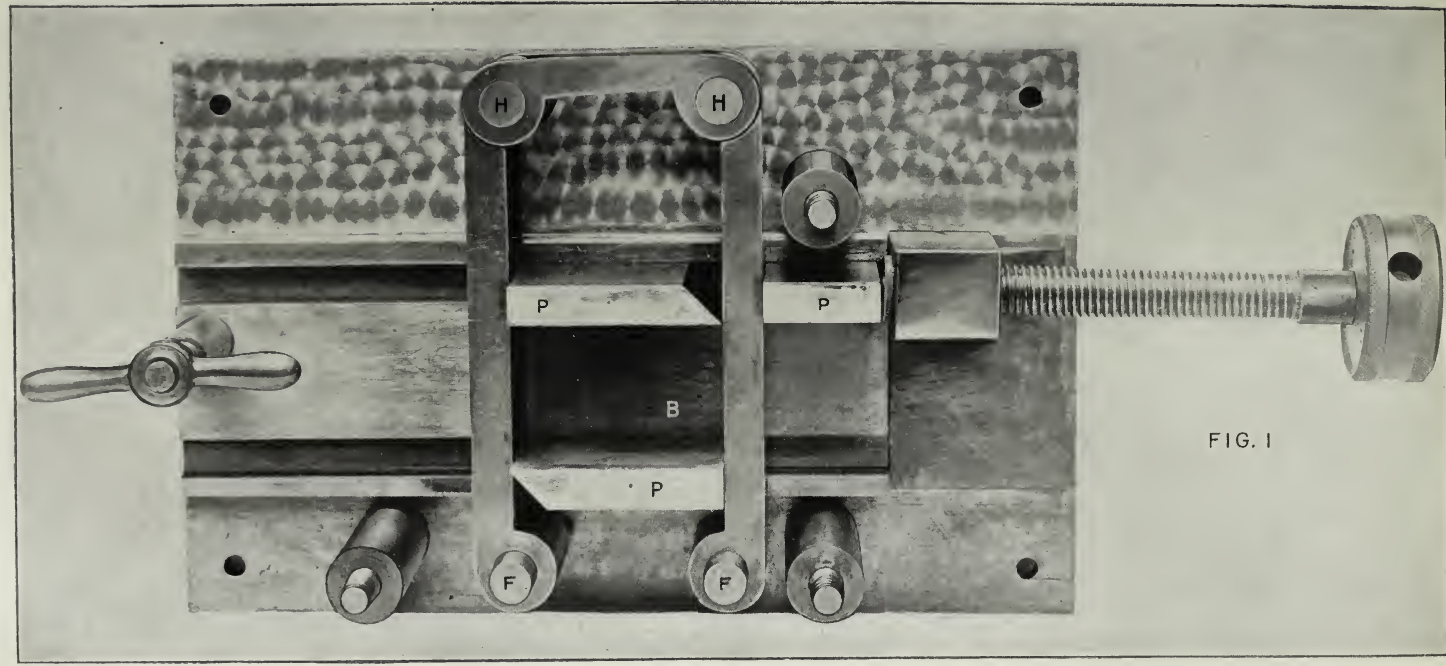

FIG. 1

SCISSION ENGINE.

pression was effected in a copying press between two heavy glass plates mounted on boards. To avoid superficial chilling of the ceresin cylinders the glass plates were warmed to approximately the same temperature as the ceresin. Good cleavage is not obtained unless the cylinders are reduced to one-third of the original length, and more nearly perfect cleavage results from still further reduction. For accurate study the compressive force should be applied to the cylinders so slowly as not to rupture the edges of the cakes by tension. The compressed cakes were placed in a mixture of ice and salt for an hour or two, and then, being held edgewise on a small anvil, were broken by striking smart blows on the edge with a light hammer.

It is best to carry out such experiments in series. Some cylinders may be pierced with a network of fine holes (fig. 5, Pl. II) and, after compression, cut across in the plane of the perforations. To get the perforations sensibly in the same plane after compression, both piercing and squeezing must be carefully done. Other cylinders, of the same dimensions but not pierced, may be compressed to the same extent as the perforated cylinders and then, after chilling, split to show cleavage. If the cylinders are squeezed too rapidly the edges will split—a contingency to be avoided because the distribution of strain then becomes irregular and eludes systematic discussion.

For experiments on scission, blocks were planed to fit the opening B as accurately as possible and the blocks were given a temperature of about 20° before straining. They were cooled and broken as in the experiments on linear compression.

Experiments with clay.—The clay used burns to a pleasing terra-cotta color, without much shrinkage. Slides of the burnt mass show that the clay contains a large amount of finely divided quartz and a small amount of black mica in minute scales. There is also a trace of organic matter in this clay, for when first heated it blackens. For use, the clay should be moistened as little as is compatible with convenient modeling and kneading.

From a well-kneaded lump of clay it is easy to cut cylinders similar to those of ceresin described above. Excellent cleavage can be produced by compressing them in a press and burning the cakes lightly in an assay muffle furnace. Indeed, to get cleavage, it is sufficient to press a pellet, say a centimeter in diameter, under a spatula and toast it over a Bunsen lamp! Yet in some respects clay is inferior to ceresin for this experiment, because cylinders, after reduction to about five-eighths of their original diameter, crack at the edges, so that the strain can not be followed systematically by the method given above. Some of these cracks are meridional and due to tension, while others occur at about 45° to the line of force and are true joints on planes of maximum tangential strain. Such a cake of clay is shown in fig. 8, Pl. II. Precisely similar cracks are produced in steel cylinders subjected to end pressure, and it is clear from these phenomena that the moist clay behaves mechanically like a true solid, relative motion of the particles taking place at an acute angle to the line of pressure. I have tried subdividing clay cylinders by a network of pin holes in one plane, and then compressing and dissecting them as described on a previous page. Up to the point where the edges begin to rupture, the deformation is exactly the same as in the cylinders of ceresin of similar dimensions and degree of compression.

On the other hand, clay behaves better than ceresin in the scission engine, apparently because I did not succeed in casting ceresin without small bubbles of included air, while it is easy to knead the clay until air is expelled. In the scission engine there is no tendency to cubical compression provided the space B is homogeneously filled, but this proviso is essential. In experiments on ceresin one acute angle of the space B is usually found empty, and though this space is never large, it is a disturbing condition. With well-kneaded clay the space B remains full after strain, and such blocks after burning show excellent cleavage.

Clay is a very instructive material to experiment upon for two reasons: Most or much of the natural slate is of argillaceous origin; and, again, the burning of the strained clay cakes may properly be considered as a true metamorphism, which nevertheless does not obliterate the cleavage mechanically induced.

Other materials tried.—Plaster of Paris pellets compressed under a spatula at just the right moment during the "setting" process and then dried out exhibit cleavage, a fact which is interesting because of the accompanying formation of selenite crystals. I have tried plaster paste in the scission engine repeatedly, but have not been able to hit exactly the right conditions. Air bubbles get into the liquid plaster while it is being poured into the space B, and if stress is applied too soon the plaster naturally sets without any development of cleavage. Moreover, plaster seems to begin to set from the outside, so that the space B was probably never homogeneously filled with a substance fitted to display the properties of homogeneous strain.

Lead cylinders pierced with holes and afterwards filled with tin wire and then compressed show by dissection just the same strains as do ceresin blocks. Such cases are shown in figs. 7 and 9, Pl. II. Similar results have been obtained with aluminium. I had hoped that these metals, cooled to the temperature of liquid air, would become brittle enough to exhibit cleavage, but was disappointed. The lead cakes seemed as tough as sole leather and I could not produce the least indication of a crack in the aluminium by the most vigorous use of the hammer.

Strain ellipsoids in ceresin.—In fig. 2, Pl. II, is shown a series of cakes of ceresin into which spherical pellets of ceresin tinged with a

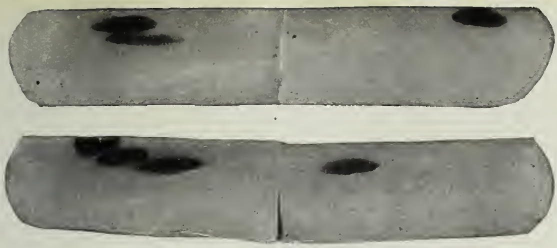

Fig. 2.

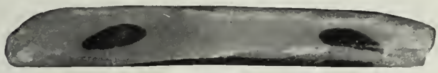

Fig. 3.

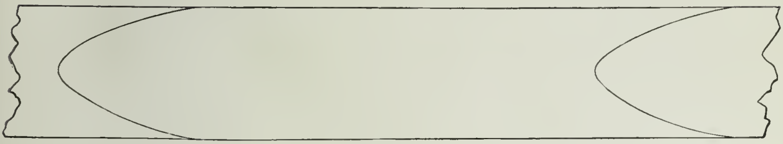

Fig. 4.

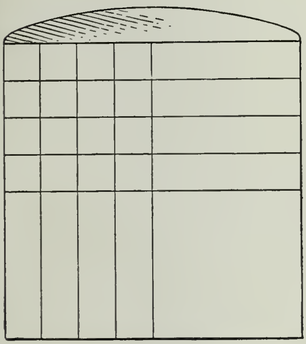

Fig. 5.

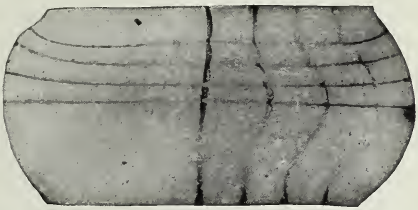

Fig. 6.

Fig. 7.

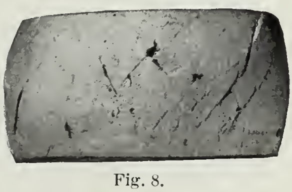

Fig. 8.

Fig. 9.

FIG. 2. STRAIN ELLIPSOIDS IN CERESIN.
FIG. 3. CLEFT STRAIN ELLIPSOID IN CERESIN.
FIG. 4. DIAGRAM OF DISTORTION IN ROLLING CLAY.
FIG. 5. DIAGRAM TO SHOW PIERCING OF CYLINDERS.
FIG. 6. CAKE OF CERESIN COMPRESSED TO TWO-THIRDS ORIGINAL HEIGHT.
FIG. 7. CAKE OF LEAD COMPRESSED TO TWO-THIRDS ORIGINAL HEIGHT.
FIG. 8. CAKE OF CLAY COMPRESSED TO TWO-THIRDS ORIGINAL HEIGHT, SHOWING PERIPHERAL RUPTURES.
FIG. 9. CAKE OF LEAD COMPRESSED TO ONE-THIRD ORIGINAL HEIGHT.

mere trace of vermilion were introduced during the process of casting. The cylinders after compression were cut radially to show the strain ellipsoids thus produced. If a composite photograph were to be taken of these and similar cases the position of the strain ellipsoid in most portions of the cross section would appear.

Many cakes containing pellets were cooled below the freezing point and split. These specimens show that the surfaces of cleavage are not parallel to the major axes of the strain ellipsoids. In some cases the cleavage developed by the hammer intersected the pellets, leaving no doubt whatever on this point (fig. 3, Pl. II). It is relatively seldom, however, that such a crack forms without splitting away a large part of the pellet and leaving some doubt as to the exact position of the major axis. Hence the observer is driven to a comparison between the dissected cakes without cracks and the split cakes. It seemed desirable, therefore, to devise a means of determining once for all the position of the strain ellipsoid in any and every part of the cake. This will now be described.

Construction of strain ellipsoids.—Fig. 5, Pl. II, is a diagram indicating the way in which cylinders were pierced with holes, forming a rectangular network covering a quarter of the cross section. A thread smeared with dry vermilion powder was drawn after the piercing needle and thus the interior of the perforations was coated with pigment.

Photographs of three cakes compressed after perforation and cut to show the network are shown on an enlarged scale in fig. 10, Pl. III. They are as nearly alike as the imperfection of the appliances used would permit. The central vertical lines in the cylinders were not absolutely central, nor were the plates between which the compression was effected accurately parallel planes. Hence, after compression the central line in each case is somewhat buckled.

From the middle one of these photographs a tracing was made, slightly modified by comparison with the other two, and then very much enlarged. In the diagram so procured ellipses were drawn by the methods explained at the end of this paper. The areas of the ellipses were next checked by a simple computation and found sensibly correct, showing that no considerable error had occurred in copying or construction. The value of the axes of the ellipses being found and the volume of the ellipsoids known, the planes of maximum tangential strain are also immediately deducible. The major axes were drawn through the ellipses and the positions of the planes of maximum tangential strain were shown by broken lines. The diagram was then reduced photographically to the same scale as the photographs from which it was derived. The result is shown in fig. 11, Pl. III.

Cleavage on the two theories.—It is now easy to draw through this quadrant of the figure representing the cross section of the cake a set of lines which are sensibly tangent to the directions of the major axes of the ellipses, and this set of lines represents the cleavages which the cake should have according to Sharpe's theory. This result is illustrated by fig. 12, Pl. III, where, for the sake of completeness, all four quadrants are filled out. Similarly a diagram can be prepared illustrating my theory, and this is given in fig. 13, Pl. III. It will be observed that the two diagrams differ very radically and that the choice between them must be an easy one.

The system of cracks likely to occur on Sharpe's theory is made sufficiently evident by the figure just mentioned. The other theory shows an interlacing of possible fractures near the center, which is more complex and could not be entirely developed in a single cake without comminution. For this reason the most probable and important fractures are given separately in fig. 14, Pl. IV.

The surfaces which at the end of the straining process are surfaces of maximum tangential strain were never at any step of the process perpendicular to the direction of greatest linear contraction. To make sure of this, I have constructed the strain ellipses for a case in which a cylinder of ceresin pierced with a network of holes was compressed to two-thirds its original length. Fig. 6, Pl. II, shows the cross section of the strained mass, and fig. 23, Pl. V, shows lines coinciding with the direction of the major axes of the strain ellipsoids for this case. Comparison of the last diagram with that previously discussed for a strain twice as great (fig. 12, Pl. III) shows their analogy, and proves the statement made in the first sentence of this paragraph.

Cleavage actually found.—It is exceedingly difficult to give satisfactory illustrations of the cleavages actually obtained by Tyndall's experiment. In the first place, the most instructive cakes are those which go to pieces under the hammer; but then the residual flakes are too delicate to be cut across radially for photographing, and were this accomplished only a single section could be figured, whereas the observer may examine them in three dimensions. Again, when the cakes are so gently hammered as merely to crack from the edges and are subsequently separated into two or more pieces, tension ruptures are produced as well as true cleavage; but these are not distinguishable in a photograph. Especially characteristic in radial section is the way in which the cleavage meets the outer edge of the cake. Seen in cross section the thinner part of the split cake at the outer edge is shaped like one horn of a crescent moon. This characteristic is shown by every cake, and yet it is not strikingly apparent in every section illustrated in figs. 15 to 22, Pl. IV, although it is well shown in several of them. The cakes break last at the axis, and here there is most danger of tension rupture in forcing the opposite portions asunder. In two or three of the specimens illustrated, however, there is evidence

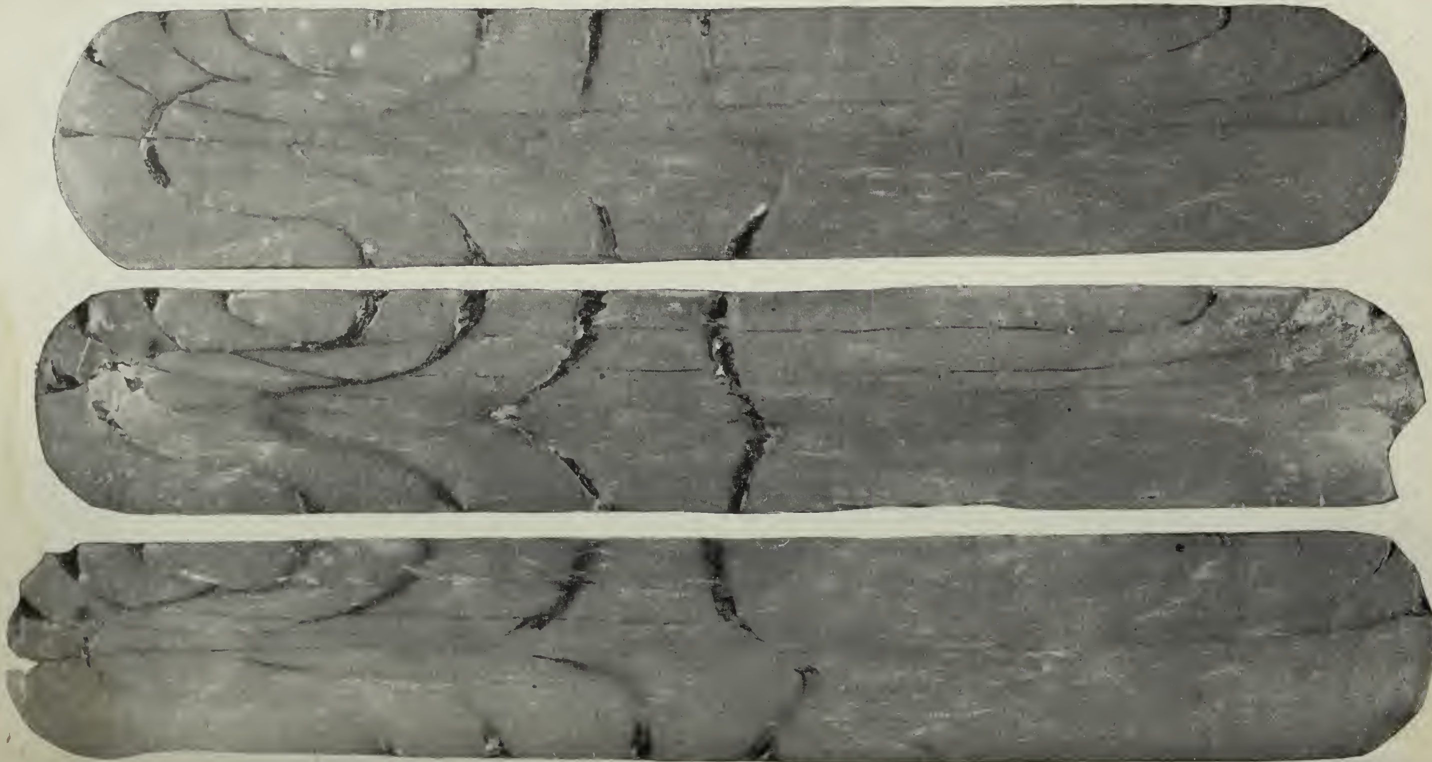

Fig. 10

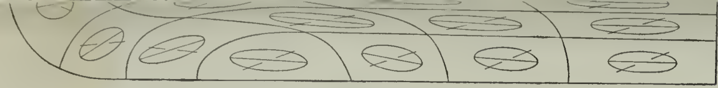

Fig. 11.

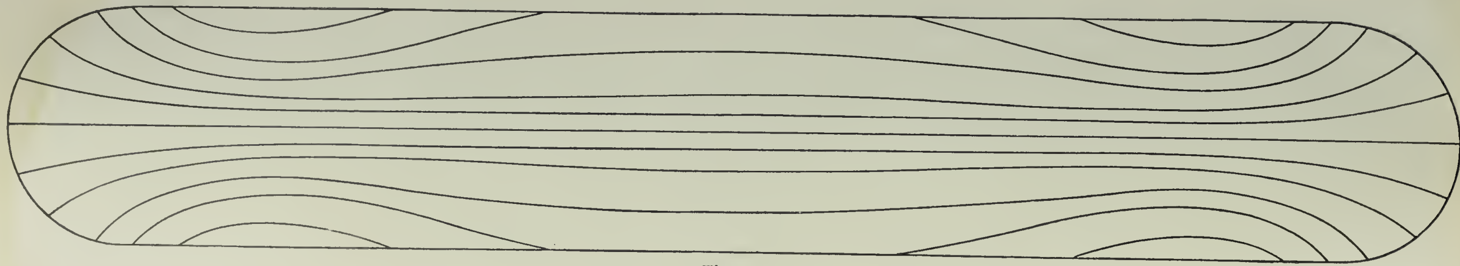

Fig. 12.

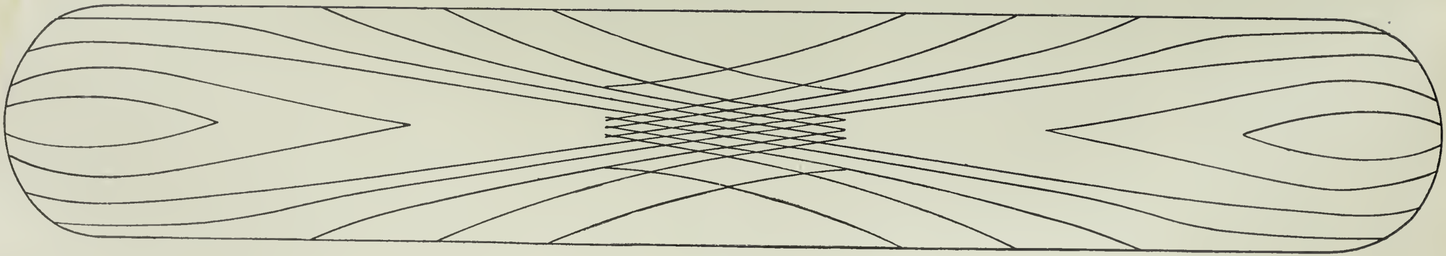

Fig. 13.

FIG. 10. THREE CAKES OF CERESIN COMPRESSED TO ONE-THIRD ORIGINAL HEIGHT, ENLARGED.
FIG. 11. DIAGRAM TO SHOW STRAIN ELLIPSOIDS IN ONE QUADRANT OF COMPRESSED CERESIN CAKE.
FIG. 12. DIAGRAM TO SHOW CLEAVAGE ON SHARPE'S THEORY.
FIG. 13. DIAGRAM TO SHOW CLEAVAGE ON BECKER'S THEORY.

of double fracture of opposite inclination at the axis (figs. 19 and 20). In figs. 18 and 21, Pl. IV, the cleavage is seen passing through the axis at an angle to the median line.

On the whole, even the photographs show a very reasonable agreement with the inference from analysis indicated as probable cleavages n fig. 14, Pl. IV. I may add that the cleavability about midway between the edge and the axis is often so perfect as to defy illustration; the flakes are frequently so thin that print can be read through hem.

I must have made Tyndall's experiment a hundred times, using wax n some occasions and ceresin on others. In no case have I broken a ake which behaved as it should on Sharpe's theory, illustrated in fig. 2, Pl. III. The section of a cake most nearly in accord with that heory which I have seen is shown in fig. 22*a*, Pl. IV, and especially or that reason. Even this exceptional instance exhibits features not agreement with that theory, while another section of the same cake ig. 22*b*) does not at all resemble the diagram constructed for the loci the major axes of the strain ellipsoid. The general features of the eavage along surfaces of maximum tangential strain seem always to recognizable when the terminations of the cylinders are plane and e compression is sufficient to produce good cleavage in the squeezed kes, but not so excessive that the minor axes of the strain ellipsoids e reduced to almost insensible length. Evidently, in order to make y instructive comparison between the two theories, these conditions ust be fulfilled.

Absence of slip cleavage.—The semitranslucency of ceresin is very vantageous for these experiments in some respects. If a cake of resin is examined in a strong light and at the same time partly ided, any internal cracks can readily be detected. When cylinders being compressed for Tyndall's experiment, between glass plates the proper temperature, the first cracks to form seem always to be the edge of the cake; and when the pressure is applied so gradually to avoid this peripheral splitting I find no internal cracks unless glass plates were too cold.

Significance of bubbles.—On the other hand, my cakes all contain nerous minute bubbles of air, carried into the mold in casting. During compression these are flattened, and are then equivalent to minute ld joints. The flattened bubbles are, of course, oriented exactly are the strain ellipsoids. They are perfectly visible in the photophs of the dissected cakes, and comparison shows that the orientan of the bubbles is indistinguishable by the eye from that of the in ellipsoids obtained by construction as shown in my diagram, 11, Pl. III. Were the bubbles smooth internally, as they would n a glass, it might be possible to dispense with the construction.

They are not smooth, however, and seem to be lined with minute paraffin crystals, so that their evidence, though confirmatory, is not sufficient.

I feel fully justified in asserting that there is in my experiments just described no blind jointing (Ausweichungsclivage) or slip cleavage in the directions in which cleavage actually takes place, or in directions called for by my theory of cleavage. But the bubbles tend to weaken the mass in the directions in which cleavage should occur on Sharpe's theory. Hence the weakening of cohesion, to which I attribute cleavage (along the surfaces of maximum tangential strain), must be so great as more than to counterbalance the effect of the bubbles.

The double or schistose cleavage which is called for by theory and is illustrated in fig. 13, Pl. III, is not often displayed except by the diversity in the directions of the surfaces of fracture near the axis of the cakes; but the fact that near the axis the cake may split in either of two directions shows that there are two intersecting cleavages.

Scission experiments.—The purpose of experimenting with scission was, as has been explained, to produce a simple strain which, if it could be made to lead to cleavage at all, would indicate beyond doubt whether the surfaces coincided with one of those of maximum tangential strain. In a scission one of these directions is parallel to two faces of a distorted rectangular mass, those, viz, which undergo no change of area. In this direction the same set of particles is subject to maximum tangential strain from the inception of the process to its completion, however long a time that may be. There is a second set of planes of maximum tangential strain, but as the strain increases in amplitude fresh sets of material particles continually replace one another in these latter planes, so that any one set of particles undergoes maximum tangential strain along these planes only for an infinitesimal time. Hence, either a smaller effect, or at least a different effect, will be produced on this second set of planes. If my theory is correct, cleavage is to be looked for only parallel to the planes of constant area, for reasons indicated in a note on the theory appended to this paper. With the unit shear, or when the acute angle of the distorted mass is 45°, the major axis of the strain ellipsoid makes an angle of about 32° ($\frac{1}{2}\tan^{-1}2$) with the undistorted planes. This strain is shown in fig. 31, Pl. VI.

Results for ceresin.—I never expected to get a perfectly smooth slaty cleavage by scission, for reasons stated in the appended note on my theory. Experiments on the scission of ceresin blocks are not very satisfactory. If the blocks have as high a temperature as I found best for Tyndall's experiment (where the strains for the most part are of much greater amplitude than my scission engine will produce), the blocks show no cleavage at all. At 20° C. and 0° C. cleavage sometimes results and is sometimes absent or insensible. When the cleav-

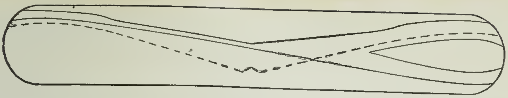

Fig. 14.

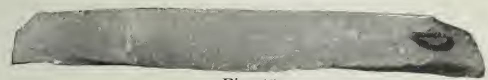

Fig. 15.

Fig. 16.

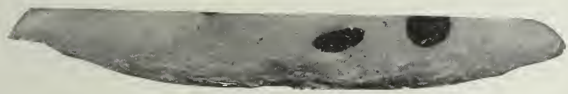

Fig. 17.

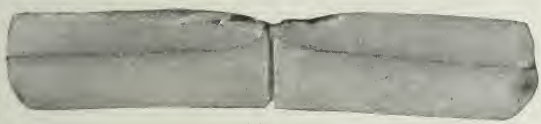

Fig. 18.

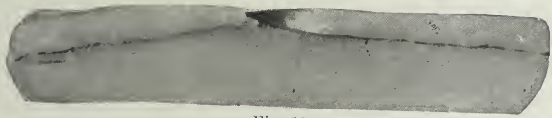

Fig. 19.

Fig. 20.

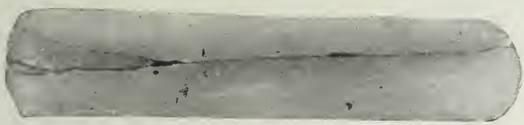

Fig. 21.

Fig. 22 *a*.

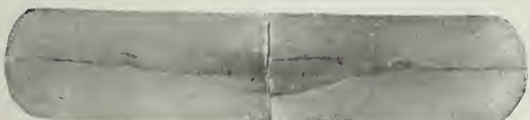

Fig. 22 *b*.

FIG. 14. PROBABLE CLEAVAGES ON BECKER'S THEORY.
FIG. 15–22. PHOTOGRAPHS OF ACTUAL CLEAVAGES.

age is a vanishing quantity or absent the mass breaks with a more or less conchoidal fracture. When there is any distinct cleavage it is parallel to the undistorted planes.

One difficulty with ceresin is that, on account of air bubbles,[a] the block does not completely and homogeneously fill the space. If it did, rupture would be impossible. In fig. 24, Pl. V, is shown an instance of rupture. The circle stamped on the block before strain is distorted to an oval which is dislocated by three tiny faults. The joints formed are exactly parallel to the undistorted plane. The truncated upper left-hand corner shows the failure to fill out the space.

In fig. 25, Pl. V, is shown a block which did not entirely fill out the space, but was not jointed like fig. 24, Pl. V. When struck on the back with a hammer it developed cracks having a tendency to parallelism with the undistorted planes. In one case, after subjecting a cake to scission, I cut off one sharp corner perpendicularly to the plane of no distortion and filled out the opposite face with a wedge, so as to reduce the block once more to a rectangle. This was again strained in the engine. After chilling it broke with some regularity. It is shown in fig. 26, Pl. V, where X is the mass which was added before the second strain.

Results for clay.—For scission clay is a far better material than ceresin, as was mentioned above, and in all the cases I have tried clay blocks subjected to unit strain and lightly burned show cleavage parallel to the planes of no distortion. A very highly instructive specimen was produced accidentally. The distorted block was dried on the water bath and then heated in an assay muffle furnace, which, however, grew hot too rapidly. The escaping water vapor burst the block into many pieces. These, fortunately, were of such sizes that it proved practicable to fit them together and restore the outlines of the block. This specimen is illustrated by a photograph (fig. 27, Pl. V). The ellipse is visible and not faulted, and the cleavage is manifestly parallel to the planes of no distortion.

Lessons drawn.—The experiments described above, which constitute a study in plasticity, appear to me to demonstrate that true cleavage (wholly free from blind joints, or Ausweichungsclivage) can be produced both in ceresin and in clay. Burning the clay does not obliterate the cleavage. The cleavage does not coincide even approximately with the direction of the major axes of the strain ellipsoids. Neither does the cleavage correspond to the position of the major axes of the strain ellipsoids at any previous stage of the strain. On the other hand, the orientation of the cleavage does correspond to the position

[a] It might be better to prepare in another way blocks of ceresin for scission. The melted mass might be very gradually cooled, with very gentle stirring, in a flat-bottomed pan, and there allowed to solidify without pouring. Then blocks could be sawn out of the mass and planed to fit the engine. Such blocks would be free from bubbles. The experiments with clay are so satisfactory that I did not try this method.

of the surfaces of maximum tangential strain. Cakes of ceresin linearly compressed exhibit and elucidate slaty cleavage near their edges. Toward their axes of symmetry they show and explain the double or multiple cleavage so characteristic of the crystalline schists. This last important phenomenon is almost unintelligible on Sharpe's theory, for if the greatest linear contraction were perpendicular to one set of cleavages in the schists, it could not also be perpendicular to the other. If it be suggested that the two (and sometimes four) cleavages were successively impressed on the schist, the answer is that observation is inconsistent with this explanation, the distribution of minerals and their mutual relations contradicting the idea. The evidence presented shows that rupture and cleavage follow the same surfaces, cleavage being due, so far as can be told, to weakened cohesion—a state of things in absolute accord with Daubrée's experiments and Heim's observation that Ausweichungsclivage and cleavage without rupture are sometimes visible in the same slide and are parallel to each other.[a] The effect of pressure in the direction of greatest linear contraction, on the other hand, is only to force molecules closer together in the line joining their centers. How this approach of molecules to one another might increase their cohesive attraction I can understand; but how it could weaken it is, to me, a mystery. So far as I know, no theory of molecular attraction has been formulated which would account for such a weakening.

The deformation of ceresin implies only a trifling expenditure of energy or a minute evolution of heat. When firm rocks are deformed, especially igneous rocks, the amount of work done or of heat evolved must be very great. That such deformation should be accompanied by the genesis of secondary minerals is in accordance with all the results of the study of metamorphism. Now, experiments of my own, not yet published, show conclusively that crystals tend to grow in the direction of least resistance, as might indeed be assumed, although they exert a linear force in any direction. Secondary minerals in a slate originating in a firm rock will thus tend to develop chiefly in the direction of cleavage. It is not improbable that the secondary development of mica on cleavage planes may further facilitate the cleavage to which it owes its existence, much as slickensides on a faulted surface facilitate further faulting. If the mica were assumed as the origin of the cleavage, it would be necessary to show how it could be generated and oriented in planes independent of the stratification without obliterating

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[a] Mechanismus der Gebirgsbildung, vol. 2, 1878, pp. 56 and 59. Heim attributes cleavage to movements (Ausweichungen) of the mass perpendicularly to the direction of pressure. It is evident that he refers to *relative* movements of adjacent portions of the mass, or what I call tangential movements. These necessarily imply forces locally inclined to the direction of the relative motion, for, in general, in any solid or in any hyperviscous liquid strained at a finite rate, a tangential displacement implies a force containing a tangential component. Heim insists that rupture and cleavage, when due to one force, are parallel, a point in which I agree with him. On the other hand, master joints and false cleavage occur characteristically at angles of more than 45° to the slaty cleavage.

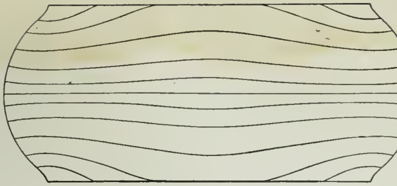

Fig. 23.

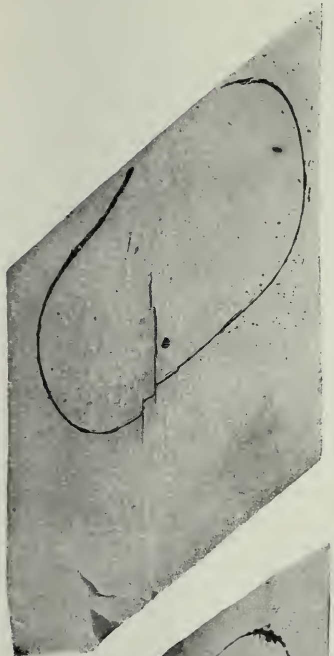

Fig. 24.

Fig. 25.

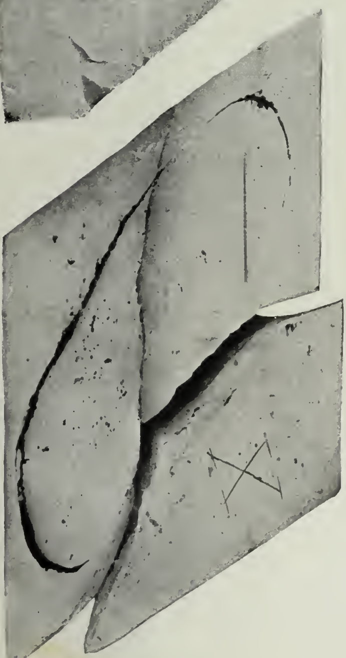

Fig. 26.

Fig. 27.

FIG. 23. LOCI OF MAJOR AXES OF ELLIPSOIDS CORRESPONDING TO FIG. 6.
FIG. 24. BLOCK OF CERESIN FAULTED BY SCISSION.
FIG. 25. BLOCK OF CERESIN SHOWING CLEAVAGE DUE TO SCISSION.
FIG. 26. BLOCK OF CERESIN SHOWING CLEAVAGE DUE TO DOUBLE SCISSION.
FIG. 27. BLOCK OF CLAY SHOWING CLEAVAGE DUE TO SCISSION.

the stratification, as well as why grit beds in slate show cleavage. This, it seems to me, has never been successfully done.

The experiments made would indicate that the order of linear compression in slates, supposing their volume inalterable, is about in the ratio of 1 to 3 or 4, and that it is accompanied by large slides or tangential strains; but the degree of strain needful to produce cleavage probably depends both on the nature of the material and on the rate of straining. From field observations I suspect that a compression of one-half sometimes suffices.

I infer that a slate belt is equivalent to a distributed fault or a step fault with infinitesimal steps, whose total displacement is of the same order as the thickness of the slate. The direction of this faulting (according to the results reached in my former discussion) is given by the intersection of the cleavage plane with a plane perpendicular to the grain of the slate, and is therefore ordinarily not greatly inclined to the horizon. Were the grain vertical it would indicate horizontal faulting. The major axis of the strain ellipsoid lies in the plane which is perpendicular to the grain of the slate but at a considerable angle to the cleavage.

The force to which cleavage is due lay in this same plane at an angle to the cleavage which would be zero if the strain were unalloyed scission, barely conceivable in nature, and finite for all other strains. There is no simple relation between the direction of the force producing strain and the directions of the axes of the strain ellipsoid for any case of rotational strain. In the case of slate the direction of the force lay within the acute angle between the direction of greatest linear compression (or the smallest axis of the strain ellipsoid) and the cleavage. In the case of symmetrically developed double or multiple schistosity, not infrequent in the crystalline schists, rotation was absent and the direction of force coincided with that of the smallest axis of the strain ellipsoid bisecting the obtuse angle between the cleavages. It appears probable, from the experiments, that the angle between the slaty cleavage and the local direction of the force to which it is due may vary within wide limits.

For other consequences of the theory confirmed by the experiments here described I must refer to my former memoir.[a]

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[a] It is easier to test the experimental results reached in this paper, now that it is written, than to examine microscopically even a very small suite of rocks. The following method of verification is suggested: Any young student or handy janitor can prepare a set of cylinders of ceresin cast at the lowest practicable temperature, with flat ends, and of a diameter equal to the length. Keep ten or twelve such cylinders in a thermostat over night at 35° C. Compress them, three at a time, between heavy, somewhat warm glass plates in a copying press to one-third of their original length, so slowly as not to burst the edges. Put the cakes in ice and salt for an hour or more. Then cut one or more of the cakes in two on a plane which includes the axis. Examination of the minute bubbles should show whether my diagram of the distribution of strain ellipsoids adequately expresses the facts. If it does so, the figures exhibiting the alternative cleavage, according to Sharpe's theory or mine, must also be correct. Split the rest of the cakes by striking them edgewise with a hammer, and compare the cleavage with the diagrams.

MATHEMATICAL NOTES.

NOTE ON THE THEORY OF SLATY CLEAVAGE.

The theory of rupture of rock masses under pressure which I have propounded[a] is that fracture occurs along planes of maximum tangential strain, or, as it is also called, of maximum slide. Cleavage I regard as due to a weakening of cohesion, antecedent to rupture, on these same planes of maximum slide, the effects being influenced by viscosity, although the direction is independent of viscosity. For the full development of this theory the reader must be referred to the former memoir, just cited, but some essential features should be included here.

The planes of maximum tangential strain in a homogeneously strained mass are readily found. Their position relative to the major axis of the strain ellipsoid is independent of the cubical compression to which the mass may have been subjected, and of any rotation which the axes may have undergone relatively to the elements of mass. These positions are therefore dependent only on the two pure undilational shears, at right angles to each other, which determine the relative magnitude of the axes of the strain ellipsoid. These two shears may be separately considered.

The first problem is, then, to find the planes of maximum tangential strain in an irrotational shear ellipsoid. In this ellipsoid the section containing the greatest and least axes is an ellipse of the same area as the corresponding great circle of the original sphère. If the radius of the circle is taken as unity, the major axis of the ellipse may be called α (the "ratio of shear") and the minor axis will be $1/\alpha$, so that all lines in the ellipse parallel to the major axis of the ellipse exceed their original length in the ratio α, and all lines parallel to the minor axis have been reduced in length in the ratio $1/\alpha$.

In the circle draw any parallelogram, for instance one with its center at the center of figure, and from the center draw two radii parallel to the sides of the parallelogram, making angles ϑ and ϑ_1 with the major axis, and meeting the circle at points $x\, y$ and $x_1 y_1$, as shown in fig. 28, Pl. VI. Then in the ellipse there will be a corresponding parallelogram and set of points which may be indicated by the same letters primed.

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[a] Finite homogeneous strain, flow, and rupture of rocks: Bull. Geol. Soc. America, vol. 4, 1893, pp. 13–90.

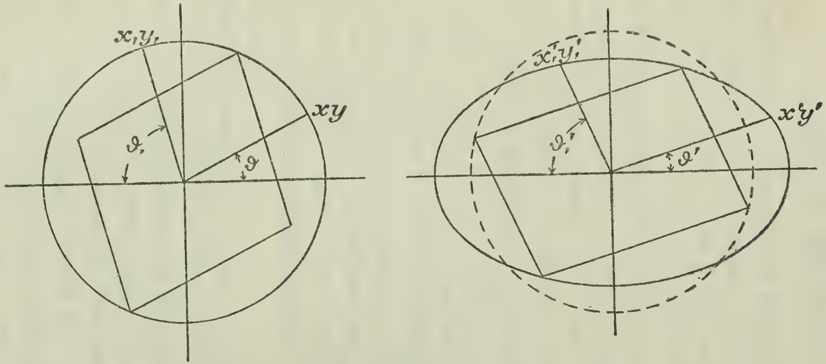

Fig. 28.

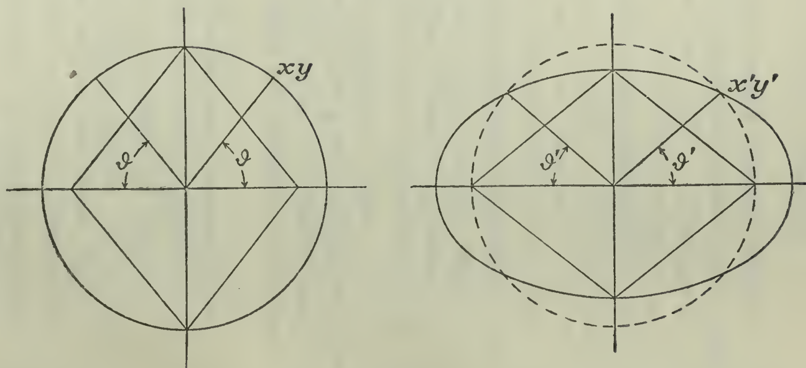

Fig. 29.

a b c

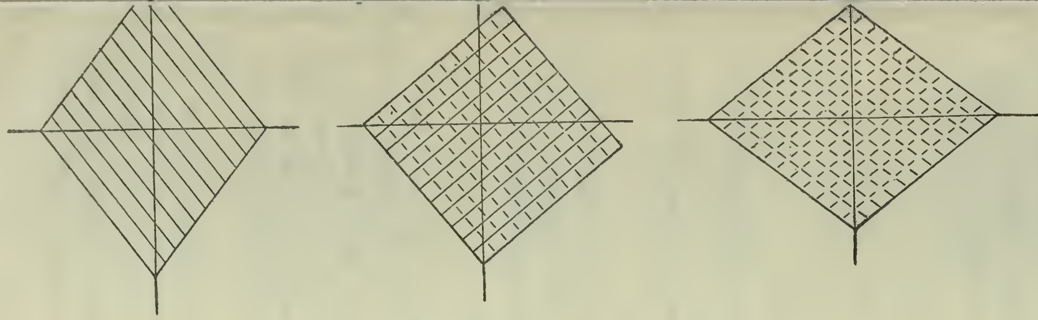

Fig. 30.

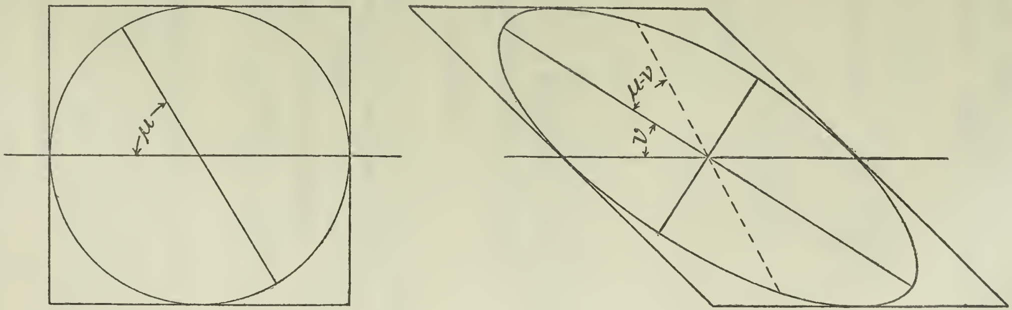

Fig. 31.

FIG. 28. DIAGRAM OF SLIDE, BUT NOT MAXIMUM SLIDE.
FIG. 29. DIAGRAM OF MAXIMUM SLIDE.
FIG. 30. PURE SHEAR COMPOUNDED OF TWO SCISSIONS.
FIG. 31. SCISSION AND ANGLE OF ROTATION μ-ν.

Now slide will change the angles of the original parallelogram, or the inclination of the radii in the circle, and the greater this change the greater the slide. If, therefore, the maximum slide is sought, the deflection of each of the two radii must be a maximum, and symmetry shows that ϑ and ϑ_1 must be equal. Hence the problem reduces to finding the radius in the circle which experiences the greatest change of direction through the strain. This is very easy, for by definition (see fig. 29, Pl. VI),

$$x'=\alpha x;\ y'=y/\alpha;$$

$$\tan\vartheta=y/x;\ \tan\vartheta'=\frac{y'}{x'}=\frac{\tan\vartheta}{\alpha^2};$$

so that

$$\tan(\vartheta-\vartheta')=\frac{\tan\vartheta\,(\alpha^2-1)}{\alpha^2+\tan^2\vartheta},$$

which has its maximum value when

$$\tan\vartheta=\alpha;\ \tan\vartheta'=1/\alpha.$$

Thus the maximum value of

$$\tan(\vartheta-\vartheta')=\frac{\alpha-\alpha^{-1}}{2}.$$

The total change of the angle of the original rhomb is measured by twice this quantity, and $\alpha-\alpha^{-1}$ is known as the "amount of shear."[a]

In polar coordinates the equation of the ellipse is

$$\frac{\cos^2\vartheta'}{\alpha^2}+\alpha^2\sin^2\vartheta'=\frac{1}{r^2},$$

and when $\alpha=\cot\vartheta'$, evidently $r=1$, so that the directions in which slide is a maximum for a single shear are those in which the radii have preserved their original length. In other words, if the circle is superposed upon the ellipse, the intersections of the two curves are the extremities of the radii in question. Hence, also, the planes of maximum tangential strain in the shear ellipsoid are the circular sections.

This subject can also be profitably considered from another point of view, that of the stresses involved. If a rod is subjected to a finite tensile load Q, I have shown[b] that the resultant stress (force per unit area), R, the normal stress, N, and the tangential stress, T, in one component shear, may be written as follows:

$$R^2=\frac{Q^2}{9}\left(\alpha^2\sin^2\vartheta'+\frac{\cos^2\vartheta'}{\alpha^2}\right).$$

$$N=\frac{Q}{3}\left(\alpha\sin^2\vartheta'-\frac{\cos^2\vartheta'}{\alpha}\right).$$

$$T^2=\frac{Q^2}{9}\left(\alpha+\frac{1}{\alpha}\right)^2\sin^2\vartheta'\cos^2\vartheta'.$$

---

[a] It would be much better to measure shear by the quantity $\frac{\alpha-\alpha^{-1}}{2}$, and to call this the *amplitude* of shear.

[b] The finite elastic stress-strain function: Am. Jour. Sci., 3d ser., vol. 44, 1893, pp. 337-356.

Comparing this value of R^2 with the polar equation of the ellipse, it appears that for any value of ϑ'

$$rR = \pm Q/3,$$

so that the resultant load or initial stress, or stress into final area, is the same on any section. Now, for the circular section, or tan $\vartheta' = 1/\alpha$, $N=0$, so that the entire load is tangential, and although the tangential stress (as is well known) is greatest for $\vartheta' = 45°$, the tangential load, $\pi r\ T$, is greatest for $\tan\ \vartheta' = 1/\alpha$, and then becomes $\pi T = \pi Q/3 = \pi R$. Thus, according to the theory here set forth, rupture and cleavage are determined by maximum tangential load, not by maximum tangential stress.

If a second shear is applied to the mass in a plane at right angles to the first, the effect in the plane of the first shear is only to reduce the height without altering the breadth. Consequently no further slide is produced in the plane of the first shear and no further tendency to the impairment of cohesion or to its dissolution exists. On the other hand, the angle of the planes of maximum tangential strain to the major axis of the ellipse is modified. If the final angle made by these planes with the major axis A, is ω, and if B and C are the other axes of the ellipsoid (A> C> B) it is easy to see[a] that in the plane AB

$$\tan^3 \omega = B^2/AC;$$

or if the mass is incompressible, so that $ABC=1$,

$$\tan\ \omega = B.$$

From the point of view of cleavage and rupture, the inner mechanism of a pure shear is important. Suppose the rhomb shown in fig. 30*a*, Pl. VI, to be divided into an infinite number of equal strips, each of length equal to a side, and that these be slid over one another as the cards of a pack can be slipped. Then the resulting figure may be a square, shown at *b*. Divide this square anew into strips at right angles to the former divisions and shift these new strips as shown in fig. 30*c*, Pl. VI. The result of the double process will be a rhomb identical with that due to pure shear, shown in the preceding diagram, fig. 29, Pl. VI.[b]

Now, not only is shear produced by this mechanism, but it seems impossible to devise any other mechanism by means of which it can be produced. The significant point is that action is almost confined to planes parallel to the sides of the rhomb; elsewhere the only relative movement which occurs is mere approach or separation of molecules on lines joining their centers. It is conceivable that the lengthen-

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[a] Bull. Geol. Soc. America, vol. 4, 1893, pp. 34 and 22.

[b] The two component strains are scissions, and it is susceptible of easy algebraic proof that if two scissions of equal amplitude are superposed in such a manner as to produce pure shear the two scission planes must be at right angles to each other. If the ratio of the resultant shear is α, the ratio of shear in each of the scissions must be $\sqrt{\alpha}$.

ing of elements parallel to the major axis should cause rupture perpendicular to this direction, or in planes parallel to the plane of the mean and minor axis. It is also true that when short cylinders are subjected to linear compression, their edges sometimes split by tension meridionally or in planes perpendicular to the plane of the two greater axes of the strain ellipsoid, and that the blocks sometimes yield along planes of maximum tangential strain. But that the approach of molecules along the smallest axis, on lines joining their centers should tend to weaken their cohesion and produce cleavage perpendicular to the smallest axis seems to me most improbable from a mechanical point of view, and I have found no experimental evidence of such an effect. Such an effect, however, is implied in Sharpe's theory of cleavage.

In a pure shear the lines of maximum tangential strain do not coincide throughout the strain with the same material particles. The first particles to undergo this strain stood originally at 45° to the line of pressure, while those which ultimately underwent maximum tangential strain originally lay at angles of less than 45° to the line of pressure— i. e., $\tan^{-1} 1/\alpha$. These lines of strain thus rotate through wedges of the strained mass. The axes of the ellipsoid, however, in any so-called pure strain coincide with the same sets of particles throughout, and maintain an invariable direction.

In rotational strains, on the other hand, the axes of the ellipsoid wander, so that successive sets of particles become axial. This rotation of the axes affects also the rotation of the lines of maximum slide. The axial rotation adds to the rotation of one set of lines of maximum slide and diminishes the rotation of the other set. Hence, in rotational strain one set of sliding planes wanders through the mass faster than the other. Consequently, also, on one side of the minor axis a given radial layer of particles is subjected to maximum tangential strain for a longer time than the corresponding layer on the other side. The angle of rotation of a strain is the angle between either axis of the strain ellipsoid and the line which passed through the same set of particles before strain began.

The extreme case of rotational strain, and the most important one, is scission (fig. 31, Pl. VI). In scission the rotation of the axes of the strain ellipsoid exactly compensates for the rotation which one set of planes of maximum strain would have in an irrotational strain of equal amount. Hence, in scission this latter set of planes does not rotate at all, or, in other words, the same set of material particles is subject to maximum tangential strain from the inception of strain to its conclusion. The other set of planes rotates through the mass just twice as quickly as it would if the strain were "pure."

Now, all real matter is viscous, and a solid displays its viscosity by yielding gradually to force up to a certain limit. A mass to which force is applied for a brief time interval resists deformation not only in virtue of its "rigidity,"[a] but in virtue of its viscosity also. Hence, in the case of rotational strains in viscous solids, those layers of particles through which the planes of maximum tangential strain move more slowly will experience greater permanent deformation than the layers on the other side of the minor axis. These last, when the difference of rotation is considerable, will either recover elastically or rupture like a brittle body, thus giving rise to master joints and false cleavage.

Hence, according to the theory here propounded, slaty cleavage will result, in suitable material, from rotational strains, and will be found on the side of the least axis of the strain ellipsoid from which rotation takes place. In other words, it will occur at an angle to the major axis, the tangent of which is the third root of B^2/AC, but at only one of the angles so defined. It does not seem probable, from a theoretical point of view, that scission by itself will produce relatively perfect or smooth cleavage. If the cleavage due to scission alone had a certain roughness, and if the mass were further subjected to a linear compression that would reduce it to a fourth of its original thickness, this roughness would also be reduced to a fourth, or the cleavage would be four times as smooth as in simple scission. Furthermore, the conditions under which scission alone is produced must be extremely exceptional among rocks. All deformations, however, can be resolved into scissions; so that, if it were to be said that cleavage is due to strains compounded of scissions, this would merely be equivalent to asserting that cleavage is due to deformation.

NOTE ON INSCRIPTION OF AN ELLIPSE IN A PARALLELOGRAM.

This problem is easily solved algebraically if, for example, the parallelogram is derived from a square by displacements. It is thus treated in my former memoir on homogeneous strain. For such discussions as have been offered in this paper it is convenient to use a graphical method.

Let the sides of the parallelogram in fig. 32, Pl. VII, be $2a'$ and $2b'$, the value of a' being greater than that of b', and let the acute angle between the sides be ψ. Draw through the center of the figure lines parallel to the sides, then these lines will be conjugate diameters of the inscribed ellipse. By the properties of conjugate diameters these are connected with the axes a and b by the two relations,

$$(a \pm b)^2 = a'^2 + b'^2 \pm 2a'\,b' \sin \psi.$$

[a] Rigidity is resistance to change of shape when the force is so gradually applied that viscosity does not come into play. Rubber is a rigid body with a low modulus of rigidity. Rigidity in this technical sense is a property common to all solid bodies.

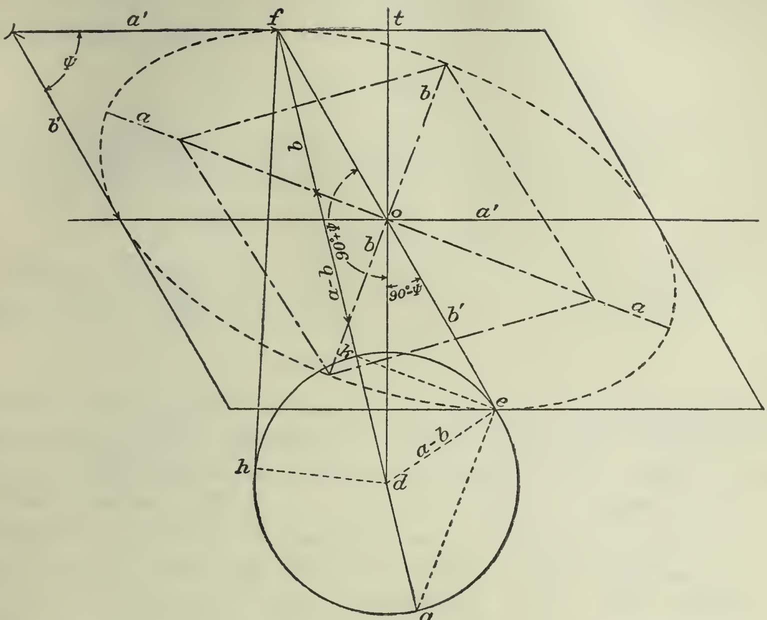

Fig. 32.

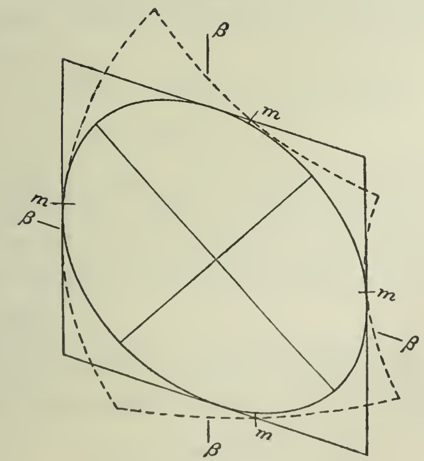

Fig. 33.

FIG. 32. INSCRIPTION OF ELLIPSE IN PARALLELOGRAM.
FIG. 33. APPROXIMATE INSCRIPTION OF ELLIPSE IN CURVILINEAR QUADRILATERAL.

From the center, o, draw a line od perpendicular to a' and of length a'. Connect the foot of b' (or the point e) with d. Then in the triangle ode the angle doe is $90°-\psi$, and therefore

$$\overline{de}^2=a'^2+b'^2-2a'\,b'\sin\psi=(a-b)^2.$$

Again draw from d to the top of the shorter conjugate diameter the line df. Here the angle fod is $90°+\psi$, and hence

$$\overline{df}^2=a'^2+b'^2+2a'\,b'\sin\psi=(a+b)^2.$$

With de as radius, describe a circle about d cutting fd at k and prolong fd to g. Then, evidently,

$$fg=2a;\ fk=2b;$$

so that the magnitude of the axes is known. To find their position, draw through o lines parallel to the chords ek and eg. The line fd will then be divided as in the ordinary construction of the ellipse, founded on the theorem that if two fixed points, on a right line, are constrained to move on rectangular axes, the curve generated by any other point on the line will be an ellipse whose greatest and least diameters lie in the given rectangular axes. The construction shows that f is a point on the ellipse. There are two positions of the axes found which are compatible with this condition, but only one which is compatible with the further condition that ft shall be tangent to the curve. Hence a is parallel to ek and b is parallel to eg.

I find that a closely analogous construction was given by Mannheim, in 1857.[a] That here presented has certain advantages.

To find the mean radius of the ellipse, draw the line fh tangent to the circle. Then

$$\overline{fh}^2=(a+b)^2-(a-b)^2=4ab;$$
$$fh=2\sqrt{ab},$$

or twice the radius required. Also the angle fdh is the acute angle between mean radii of the ellipse. If the length $\sqrt{ab}$ is set off on a, and lines are drawn from this point to the extremities of the minor axis, they will be parallel to the mean radii and correspond to the sides of the rhomb in fig. 29.

If only the position of the axes in the rhomb is wanted, it can conveniently be found as follows without determining the magnitude of the axes. Let ϑ be the angle between a and a'; then

$$\tan 2\vartheta=\frac{\sin 2\psi}{\cos 2\psi+a'^2/b'^2}.$$

To prove this equation, write the equation of the ellipse referred to its conjugates as axes in the well-known form $x'^2/a'^2+y'^2/b'^2=1$. If x and

[a] See Williamson's Diff. Calc., 9th ed., p. 374.

y are abscissa and ordinate of a point on the ellipse referred to rectangular axes, one of them containing a',

$$y' = y/\sin\psi;\ x' = x - y/\tan\psi.$$

Substitution gives an equation of the ellipse in rectangular coordinates equivalent to

$$a_{11}x^2 + 2a_{12}xy + a_{22}y^2 = 1,$$

and it is well known that

$$\tan 2\vartheta = \frac{2a_{12}}{a_{11} - a_{22}},$$

which gives the value stated above. This value may be old, but I do not recall having seen it.

When it is desirable to draw the strain ellipse characteristic of the central point of a curvilinear quadrangle representing a small portion of a strained mass, a rational method which can not be very erroneous is as follows: In fig. 33, Pl. VII, at the central points, m, of two opposite curved sides draw tangents and from their intersection a line, β, bisecting the angle between the tangents. Proceeding in the same way with the other two curvilinear sides, find a second bisectrix. Next draw through the middle points, m, of the curvilinear sides lines parallel to the bisectrices. These parallels form a parallelogram in which, as shown above, it is easy to inscribe an ellipse, which, however, may not make an exact contact with the curved sides, though it usually approaches closely to contact.

To examine the legitimacy of this construction, suppose that not merely the sides were given but a large number of intermediate curves. Then at the center there would be a small parallelogram whose sides would have directions intermediate between the tangents at the points m. Evidently the simplest hypothesis is that the directions of these sides would each be the mean of those of the two opposite tangents, and this assumption is made in the construction. Though the spacing of the intermediate curves would in general vary, it is perfectly legitimate to assume that for small distances the spacing would vary linearly, so that in the central parallelogram points corresponding to m would lie at distances apart which are simply proportional to those of these points on the curvilinear quadrangle. No further assumption is made in the construction, and I can see no doubt that it is sufficiently accurate for any such purpose as that to which it has been applied in the foregoing paper.

NOTE ON COMPUTATION OF TAN ω.

Let a, b, c be the axes of the strain ellipsoid, c being vertical to the plane of the diagram, and let $r^3 = abc$. If x is the original distance of point from the axis of the cylinder and x' the final distance of the ame point from the axis of the compressed cake,

$$\frac{c}{r}=\frac{2\,\pi\,x'}{2\,\pi\,x}=\frac{x'}{x},$$

$$\frac{rx'}{x}=\frac{r^3}{ab}=c,$$

$$\pi\,ab=\pi\,r^2\,\frac{x}{x'},$$

e area of the ellipse. In preparing fig. 11, Pl. III, I found that the ipses obtained by construction agreed very fairly with the last rmula. The differences seemed due to slight inaccuracy in reproing the network of curved lines in the dissected cakes, fig. 10, Pl. III. The angle ω is given by

$$\tan^2\omega=\frac{b^2}{r^2}=\frac{x}{x'}\,\frac{b}{a},$$

f A and B are the axes found by construction, and if it is assumed $B/A=b/a$,

$$\tan\omega=\sqrt{\frac{x}{x'}\,\frac{B}{A}}=\frac{b}{r},$$

$$\sqrt{\frac{x}{x'}\,\frac{A}{B}}=\frac{a}{r}.$$

fig. 11, Pl. III, the ellipses are plotted from the computed axes, ellipticity and orientation being derived from the construction. a very minute examination would distinguish this from a diagram nding solely on construction.

NOTE ON VOLUME CHANGES IN THE FORMATION OF SLATE.

some theories of slaty cleavage, cubical compressibility of the is invoked to explain certain phenomena; but it seems very ful to me whether this can play any notable part in the process te making. In plastic deformation a mass must first be strained elastic limit, at which there is a cubical compression correspondthe intensity of the force (or to the stress) needed to produce this . When the stress is increased above this limit plastic deformats in and is attended by no further change of volume. Thus the change of volume is a function of the stress at the elastic limit, and the cubical compression is one-third of this stress divided by the modulus of compressibility.

Now, slates are in part derived from structureless shales which, at any considerable distance beneath the surface, are moist. Their compressibility must be intermediate between that of water and that of their mineral components. Other slates, again, are produced from firm rocks like granite. The moduluses of compression of shale and granite are not known; that of water is 21×10^6 grams per square centimeter; that of quartz, 387×10^6 (Voigt), and that of glass from 347×10^6 to 437×10^6 (Everett). Again, the breaking strain of concrete under compressive loads is from 80,000 grams per square centimeter upward, and that of granite is 1,006,000 (v. Bach). Of course the elastic limit is lower than the breaking strain. Now, if shale is as strong as an inferior concrete and as compressible as water, the cubical compression at the elastic limit will be

$$\frac{.08\times10^6}{3\times21\times10^6}=.0013;$$

and if granite is as compressible as quartz, the cubical compression when it begins to flow will be

$$\frac{1.006\times10^6}{3\times387\times10^6}=.00087.$$

In each case the cubical compression (which is three times the linear compression) turns out nearly one-tenth of 1 per cent, a quantity the evidences of which it would be very difficult to trace in the field. It seems to me that the change in volume of shales and granites must be of this order, and that, for most purposes, they may be regarded as incompressible.

Doubtless the metamorphism and hydration of slate is attended by changes in density; but densities of 2.60 to 2.80 appear to include some clays, all the clay slates and phyllites of which I have a record, and the more typical granites. These densities thus afford no evidence that considerable increase in density attends the development of cleavage.

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PUBLICATIONS OF UNITED STATES GEOLOGICAL SURVEY.

[Bulletin No. 241.]

The serial publications of the United States Geological Survey consist of (1) Annual Reports, (2) Monographs, (3) Professional Papers, (4) Bulletins, (5) Mineral Resources, (6) Water-Supply and Irrigation Papers, (7) Topographic Atlas of the United States—folios and separate sheets thereof, (8) Geologic Atlas of the United States—folios thereof. The classes numbered 2, 7, and 8 are sold at cost of publication; the others are distributed free. A circular giving complete lists may be had on application.

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