MEMOIR No. 38

NORTH AMERICAN CORDILLERA

FORTY-NINTH PARALLEL

BY

REGINALD ALDWORTH DALY

PART II

GEOLOGICAL SURVEY
DEPARTMENT OF MINES
OTTAWA
1912

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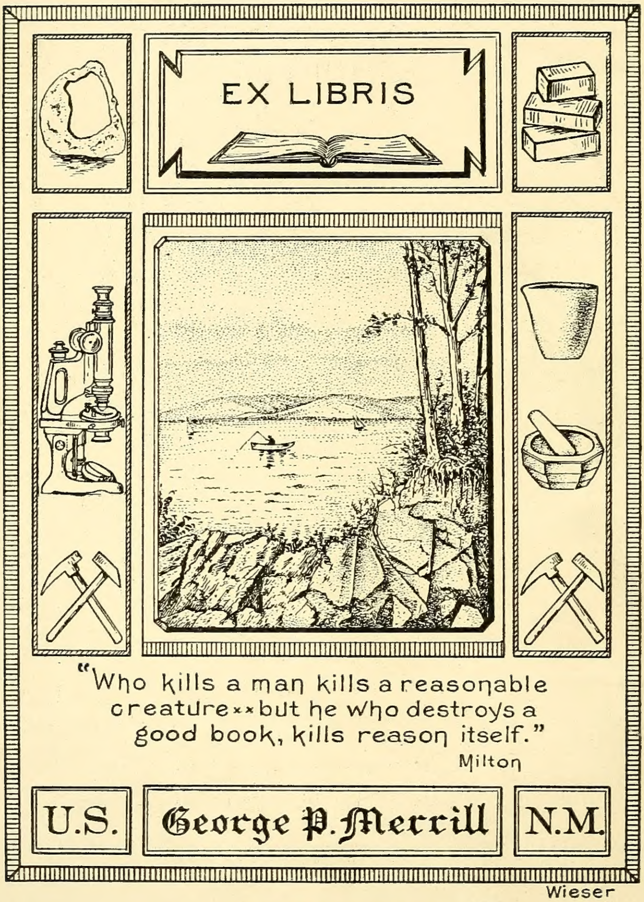

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MEMOIR No. 38

GEOLOGY

OF THE

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AT THE

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BY

Reginald Aldworth Daly.

IN THREE PARTS

PART II.

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INTRODUCTORY.

Through the courtesy of W. F. King, C.M.G., LL.D., B.A., D.T.S., Chief Astronomer, Department of the Interior, the Geological Survey is enabled to publish this Memoir. The field work was done under, and at the expense of, the International Boundary Commission, and appears as an appendix to the report of Mr. King, the Canadian Commissioner. As the report constitutes a most important contribution to the geology of western Canada, and as in its 'Blue Book' form it would not be available for many libraries and individuals that would have use for it, Dr. King kindly consented to allow the Geological Survey to print it as a Geological Survey Memoir, and thus secure for it adequate distribution in geological quarters.

The Geological Survey is pleased to be able to add to its list of Memoirs this work that deals with the geology of such a long and important section through the Western Cordillera. It must be referred to constantly in future work dealing with the geology of British Columbia, and were it not available in the publications of the Survey great loss and inconvenience would result.

(Signed) **R. W. Brock,**
Director.

GEOLOGICAL SURVEY,
OTTAWA, October 21, 1912.

APPENDIX 6.

REPORT OF THE CHIEF ASTRONOMER, 1910

GEOLOGY

OF THE

NORTH AMERICAN CORDILLERA

AT THE

FORTY-NINTH PARALLEL

BY

REGINALD ALDWORTH DALY.

IN THREE PARTS

PART II

LETTER OF TRANSMITTAL.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY,
BOSTON, MASS., April 30, 1910.

W. F. KING, Esq., C.M.G., B.A., LL.D.,
Commissioner for Canada, International Boundary Surveys,
Ottawa.

SIR,—I have the honour to submit the following report on the Geology of the mountains crossed by the international boundary at the Forty-ninth Parallel. The report is based on field-work carried on during the seasons of 1901 to 1906, inclusive. To yourself, under whose direction the whole work has been done and from whom I have received help in many ways, I beg to tender my sincere thanks.

I have the honour to be, sir,
Your obedient servant,

REGINALD A. DALY.

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PART III

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CHAPTER XIX.

CORRELATION IN THE WESTERN GEOSYNCLINAL BELT.

In following the section along the International Boundary we have crossed the 'grain' of the Cordillera and, in consequence, have tended to find the maximum number of distinct formations in our path. On the other hand, the narrowness of the belt which has been mapped affords a relatively small chance for the discovery of fossiliferous or other horizons which can be used for direct correlation of the formations with the standard systems. Correlation of the rocks actually studied within the different mountain ranges is, thus, a matter of no little uncertainty. In face of that difficulty it will be well briefly to review the principles on which the writer has ventured to make the correlations so far stated. It need scarcely be stated that many of the assignments of the formations of the eastern ranges to definite geological dates have been made in light of information won from the western ranges. Owing to the construction of the preceding part of this report many of these considerations have not been expressly stated; it has seemed better, for the sake of brevity, to concentrate such arguments in the following table of correlations with its accompanying explanation.

Principles Used in Correlation.

The principles on which the correlation of the formations occurring in the Boundary belt, has been based, include some which are obvious and commonly used; others are open to more or less debate.

1. *Fixed horizons.*—These include the Cultus formation (Triassic), the Chilliwack series in large part at least (Upper Carboniferous), the Pasayten series (Cretaceous, Shasta-Chico), the Kettle River formation (Oligocene), the limestone-quartzite series at Rossland and Little Sheep Creek valley (Carboniferous). The Huntingdon formation at the western end of the section is fossiliferous and probably of Eocene (Puget group) age. The younger argillite of Little Sheep Creek valley south of Rossland is fossiliferous and doubtless Mesozoic.

2. *Relation to the Rocky Mountain Geosynclinal.*—At the summit of the Selkirks the Cambrian and conformable pre-Olenellus formations plunge underground, never to reappear farther west. At least, no rocks which, with any degree of plausibility, can be lithologically correlated with the Summit series have yet been seen at this latitude west of the Columbia river. The reason for the failure of these formations in the west has been stated in chapter VIII. It

is clear that, if the zone of Cambrian and 'Belt terrane' shore-lines was situated in the vicinity of the Columbia river and a large region to the west thereof furnished the clastic material for the Rocky Mountain Geosynclinal, we must not expect to find Cambrian or older marine sediments conformable with the Cambrian in the mountains west of the river (Columbia system and probably the Cascades).

3. *Lithological similarities.*—This principle has been the one most used. The fossiliferous Huntingdon, Cultus, Pasayten, and Kettle River formations have, respectively, only one occurrence in the Boundary belt; they cannot, therefore, be used extensively in the direct discovery of horizons in the more widely-spread rocks. The great majority of the latter, however, belong to a number of heterogeneous series, from the Pend D'Oreille group of the Selkirks to the Chilliwack series of the Skagit range. Each series, lithologically variable in itself, has very close resemblance to each of the others. The series at nearly the extreme east (Rossland district) carries Carboniferous fossils; the series at the extreme west (Chilliwack district) likewise carries Carboniferous fossils. The correlation of only a few of these series is imperative; for all of them it is merely permissible until paleontological evidence is added to the lithological evidence.

4. *Correlation of the Forty-ninth Parallel formations among themselves, aided by comparison with standard, fossiliferous sections to north and south.*—The general correlation of the rocks occurring in the Western Geosynclinal Belt will be discussed on later pages but it may here be noted that the continuance of the Paleozoic belts along their strike brings them into areas where Carboniferous fossils have been found in greater or less abundance and always in terranes much like those represented in the Pend D'Oreille, Attwood, Anarchist, and Chilliwack series. Examples are: the Cache Creek series of the Kamloops district, the Slocan series of the Slocan district, the Wood River series of western Idaho, and the Calaveras series of California.

5. *Correlation of the sedimentary rocks often suggested through the accordant testimony of the relative dates of deformation, metamorphism, and igneous intrusion.*—*a.* The periods of severe, though not always general orogenic movements which have been proved elsewhere in the Cordillera, are: the pre-Cambrian, Upper Jurassic, early Eocene (post-Laramie), and the later Miocene. It seems already highly probable that, with the possible exception of orogenic events in the mid-Carboniferous and at a pre-Devonian, post-Cambrian time, no other periods of strong general deformation will be proved for the Western Geosynclinal Belt through future discoveries, at least so far as concerns the post-Cambrian formations.

b. Extreme regional metamorphism in this belt, where not increased by the contact-metamorphism of intrusive bodies, is a fairly general indication of the pre-Cretaceous age of the rocks so altered. Wherever the Jurassic or Triassic formations are associated with Carboniferous or other Paleozoic formations within the Western Geosynclinal Belt, the Mesozoic beds are almost always less notably changed by regional metamorphism than are the adjacent Paleozoics. The above-mentioned series, occurring in the Forty-ninth Parallel section and here referred to the Paleozoic, show those degrees of regional metamorphism which characterize the Carboniferous terranes of Alaska, British Columbia, Idaho, and California. At the same time it must not be forgotten that the Forty-ninth Parallel section runs through a part of the Western Geosynclinal Belt of the Cordillera where igneous intrusion has been specially effective. It is, therefore, quite possible that both Triassic and Jurassic beds are included in one or more of the Pend D'Oreille, Attwood, Anarchist, or Hozomeen series. However, it is probable that, in the areas mapped under the first three names, post-Jurassic sediments do not occur.

c. With very few exceptions the law holds for the world that batholithic (and stock) intrusion of granites and more mediosilicic plutonic rocks is directly preceded by specially severe orogenic movements. Combining this principle with that noted under *a,* it is often possible to obtain valuable indications as to the age of the intrusive bodies so dominant on the Forty-ninth Parallel. Such suggestions can sometimes throw light on the age of associated sediments.

Similarly with proper caution, one may use the degree of metamorphism of igneous intrusive bodies as pointing with more or less probability to their dates of intrusion. For example, the Castle Peak stock, cutting upturned Upper Cretaceous strata, is certainly post-Cretaceous in age. It is not at all crushed or sheared and seems, therefore, not to have suffered the squeezing which this whole region underwent in the Miocene. (See Smith and Calkins, Snoqualmie folio, U.S. Geological Survey, 1906). The intrusion of this stock is therefore best referred to the later Miocene or Pliocene. As above noted this correlation is confirmed on other grounds.

6. *Lithological resemblances among igneous rocks.*—This principle can obviously be used only with great care, but when it is applied along with all the others, it can give immediate and valuable results. Many tentative correlations on this basis have been described in the body of the report.

7. *Consanguinity among the igneous rocks an aid to correlation.*—To a student of petrology there is little difficulty in believing that probable correlations can often be made among adjacent igneous bodies which show, in their composition, that they have been formed by mutual differentiation. They may differ slightly in age but, perhaps with few exceptions, by only a small fraction of a geological period for each group of bodies so compared. At the end of that relatively brief period the igneous complex is frozen, and in most cases the next invasion of magma has different composition and runs through a somewhat different cycle before it too crystallizes. Consanguineous bodies are likely, therefore, to be nearly of the same geological age. Partly on this ground several correlations have already been made; for example, the Slesse diorite and Chilliwack granodiorite; the Castle Peak granodiorite and the adjacent bodies of syenite porphyry; the Similkameen and Cathedral batholiths; the Coryell syenite batholith and the syenite-porphyry chonoliths, dikes, sheets, etc., of the

Rossland and Midway mountains; the Rossland latites and monzonite; and the Bayonne granodiorite batholith, and the satellitic stocks of biotite granite to the southwest.

CORRELATION AMONG FORMATIONS AT THE FORTY-NINTH PARALLEL.

Using these various principles the writer has constructed the following table (XXXIV) of correlation for the formations traversed between the Purcell Trench at Porthill and the Gulf of Georgia. It is seen that the argument for the general correlation is a dove-tailed combination which is stronger than would be a classification founded on a much smaller number of principles. The writer believes it to be considerably stronger than would at first sight seem possible in view of the very few fossiliferous horizons actually discovered on the Forty-ninth Parallel. Much of the correlation would be impossible without the aid of earlier work done in the regions to north and south of the Boundary line; the cumulative evidence of such results together with the many facts detailed in the preceding chapters, has prompted the constructive scheme shown in this table.

In this and the following correlation tables the formations in any compartment are listed in order of age, where possible, but in many cases this could not be accomplished.

A brief list of the more doubtful references stated in the table will be of convenience, although a fuller account of the problem in each case must be sought in the descriptions of the preceding chapters.

Further information is needed concerning the paleontology of the sediments interbedded with the Beaver Mountain and Rossland volcanic groups. Direct paleontological evidence is greatly needed for the correlation of the Pend D'Oreille group as mapped east of the Columbia river, as also for the correlation of the Attwood, Anarchist, and Hozomeen series. The lower beds of the Chilliwack series are as yet quite unfossiliferous and, on account of the relatively low degree of metamorphism of the Paleozoics in the region west of the Chilliwack batholith, there is reason to hope that fossils may be found in that interesting part of the series. The apparently unconformable position of the Tamihy series upon the Chilliwack (Upper Carboniferous) beds needs to be confirmed by further study; the relation of the Tamihy series to the Cultus (Triassic) formation should, if possible, be determined. Among the igneous bodies, greatest doubts are felt as to the dates of the Rykert, Trail, Cascade, Osoyoos, and Remmel batholiths, the Rossland and Beaver Mountain volcanics, and the Skagit volcanic group. All of these bodies are specially mentioned on account of their quantitative importance as well as on account of their general relations to the historical geology of the Cordillera. Full of errors as the table may be, the writer is impelled to publish it with the hope that it may be of some aid to future workers in the geology of the region. Upon them will inevitably fall the burden of constructing a time-scale to fit the many events recorded in the huge complex of the Western Geosynclinal Belt; for those geologists a general stratigraphic scheme, though it may contain many mistakes of correlation, may be better than none at all. For convenience in printing, the table is somewhat more hard-and-fast in its statements than are the partial tables appended to the various chapters of description. All of them should be checked, for the individual details, by the text of the corresponding chapters.

TABLE XXXIV—*CORRELATION AT THE FORTY-NINTH PARALLEL.*

—	SELKIRK RANGE.	ROSSLAND MOUNTAINS.	COLUMBIA SYSTEM WEST OF CHRISTINA LAKE, AND ANARCHIST PLATEAU.	OKANAGAN RANGE AND KRUGER MOUNTAIN PLATEAU	HOZOMEEN RANGE.	SKAGIT RANGE.
Pleistocene.	Alluvium. Glacial drift.	Alluvium. Glacial drift.	Alluvium. Glacial drift.	Alluvium. Glacial drift. Dikes of basalt, andesite and porphyrite.	Alluvium. Glacial drift.	Alluvium. Glacial drift.
Miocene.	Salmon River monzonite stock. Bayonne granodiorite batholith.	Granite porphyry dikes. Syenite porphyry dikes and chonolith. Syenite aplite and camptonite dikes. Missourite dike. Coryell syenite batholith.	Flows of 'shackanite' lava. Rhomb-porphyry chonolith, sills, dikes and flows. Pulaskite porphyry sills and dikes; trachyte flows.	Cathedral granite batholith of two phases. Park granite stock. Similkameen granodiorite batholith of two phases.	Syenite-porphyry chonolith. Castle Peak granodiorite stock. Lightning Creek diorite stocks. Porphyrite sills and dikes in Pasayten sediments.	Diabase dikes in Chilliwack batholith (post-Miocene ?) Camptonite and syenite porphyry dikes in Chilliwack batholith. Syenite porphyry (?) dikes (?) cutting Huntingdon formation. Monzonite stock cutting Skagit volcanics. Chilliwack granodiorite batholith. Slesse diorite (stock ?)
Oligocene.	?	?	Mica and hornblende andesites, Midway district. Basalt and augite andesite. Kettle River formation.	?	?	Skagit harzburgite intrusion. Dunite dikes and (in part) gabbro dikes cutting Chilliwack series. Skagit Volcanic series. (All possibly Eocene.)

Eocene (?)	Sheppard granite stocks and dikes. Some aplites and lamprophyres ? Beaver Mountain Group *(Mesozoic ?)*	Sheppard granite stocks and dikes. Some aplites and lamprophyres ? Conglomerates, Sophie Mountain, etc.?		Kruger alkaline body?	?	Huntingdon formation.
Cretaceous.	?	?	?	Pasayten series, sediments. Pasayten Volcanic formation.	Pasayten sediments (members *B* to *L*). Pasayten Volcanic formation (member *A* of series).	Tamihy series.
(Mesozoic.)	Aplites and lamprophyres. *(Eocene ??)* Trail granodiorite batholith. *(Eocene??)* Rykert granite batholith. Monzonite dikes cutting Pend D'Oreille group. Younger lavas and pyroclastics mapped as Rossland group. Gabbro and basalt dikes cutting Pend D'Oreille group.	Aplites and lamprophyres. *(Eocene??)* Trail granodiorite. *(Eocene ??)* Granite stock east of Cascade. Latites of Rossland group. Rossland monzonite Shonkinitic rocks; hornblendite at Columbia river. Dunites; harzburgite. Baker gabbro and peridotite. Fife gabbro. Much andesite and basalt mapped as Rossland group, with sedimentary inter-beds. Fossiliferous beds at Little Sheepcreek?	Granodiorite stocks of 'Boundary Creek district.' Smelter granite stock. Cascade gneissic batholith. Rock Creek granodiorite. Osoyoos granodiorite batholith. Rock Creek gabbro and diorite. Dunite (serpentine) of 'Boundary Creek district.' Phoenix Volcanic group.			
Jurassic.	?	?	?	Remmel granodiorite batholith. Osoyoos granodiorite batholith.	Remmel granodiorite batholith.	Sumas granite (stock?) Sumas diorite (stock ?) Custer granite-gneiss (pre-Cambrian ?)

TABLE XXXIV—*CORRELATION AT THE FORTY-NINTH PARALLEL.—Con.*

—	Selkirk Range.	Rossland, Mountains.	Columbia System West of Christina Lake, and Anarchist Plateau.	Okanagan Range and Kruger Mountain Plateau.	Hozomeen Range.	Skagit Range.
Triassic.	?	?	?	?	?	Cultus formation.
Carboniferous older ? (and Including also Triassic ?)	Pend D'Oreille group and oldest traps mapped as Rossland group.	Pend D'Oreille group and oldest traps mapped as Rossland group. Limestone, chert and quartzite of Little Sheep creek valley. Sutherland schist complex.	Dunite, Rock Creek district. Attwood series; Anarchist series. Chlorite and hornblende schists of 'Boundary Creek district.' Grand Forks schists.	Chopaka basic intrusives. Anarchist series. Basic Complex. Ashnola gabbro.	Serpentine, Mt. Hozomeen. Hozomeen series.	Vedder greenstone (intrusive). Hozomeen series. Chilliwack series, including Chilliwack Volcanic formation.
Devonian.	?	?				
Silurian.	?	?				
Middle Cambrian ?	Sill of abnormal hornblende granite in Kitchener formation. Gabbro sills and dikes in Priest River terrane.					
Cambrian and Beltian.	Summit series; Kitchener formation.					
Pre-Cambrian.	Priest River terrane.					

CORRELATION WITHIN THE WESTERN GEOSYNCLINAL BELT.

Even a superficial comparison of the older reports on the geology of California, Nevada, Oregon, and southern British Columbia with the newer results won in Alaska, Washington, Idaho, and British Columbia, as well as on the Forty-ninth Parallel, suffices to show that the geological development has been remarkably similar all along a broad coastal zone from northeastern Alaska to southern California. This relative uniformity in the history of the large and extremely complicated zone has long been recognized in a qualitative way. More or less explicitly the idea has often been expressed in the literature that this western zone stands in vital contrast to the somewhat wider band of rocks extending from northern Alaska to Arizona and generalized in the present report under the name 'Eastern Geosynclinal Belt.' The facts obtained during the six seasons of field work on the Forty-ninth Parallel tend to confirm these broader views of the earlier students of the Cordillera, and it seems useful to note some of the principal correlations within the western zone, here called the 'Western Geosynclinal Belt.'

The work of constructing the general correlation table (XXXV) has been greatly facilitated by the recent publication of Brooks's 'Geography and Geology of Alaska,'* Dawson's 'Geological Record of the Rocky Mountain Region in Canada,'† the various folios published to date by the United States Geological Survey on areas in Washington, Oregon, and California,‡ and among the special papers, a valuable one by Diller and Stanton on the Shasta-Chico Series.§

The correlation may prove to be erroneous at certain points but the general truth that formations older than the Upper Carboniferous seem to be extremely rare in the Western Geosynclinal Belt, may be definitely stated. The apparent rarity may, of course, be partly due to the heavy metamorphism which characterizes the belt from one end to the other. On the other hand, it has been proved that the Devonian and Silurian sediments where actually found, are comparatively thin, and we have already seen that during the very long Cambrian-Beltian period of continuous sedimentation in the Eastern Geosynclinal Belt the Western Belt must have been largely out of water and suffering erosion. The oldest Paleozoic beds which play so important a role in the Eastern Belt should not be expected in the Western except, perhaps, in the form of local transgression deposits. The same reasoning may in a measure be applied to much of the Devonian period during which clastic materials, derived from

* Professional Paper No. 45, U.S. Geol. Survey, 1906, by A. H. Brooks.

† G. M. Dawson, Bull. Geol. Soc. America, Vol 12, 1901, p. 57.

‡ Snoqualmie folio (G. O. Smith and F. C. Calkins, 1906); Ellensburg and Mount Stuart folios (G. O. Smith, 1903 and 1904); Tacoma folio (B. Willis, 1899); Roseburg, Coos Bay and Port Orford folios (J. S. Diller, 1898, 1901 and 1903); Jackson folio (H. W. Turner, 1894); Smartsville folio (W. Lindgren and H. W. Turner, 1895); Lassen Peak folio (J. S. Diller, 1895); Pyramid Peak and Truckee folios (W. Lindgren, 1896 and 1897); Sonora folio (H. W. Turner and F. L. Ransome, 1897); Downieville and Bidwell Bar folios (H. W. Turner, 1897, 1898); Big Trees folio (H. W. Turner and F. L. Ransome, 1898); Colfax folio (W. Lindgren, 1900); Mother Lode District folio (F. L. Ransome, 1900); and Redding folio (J. S. Diller, 1906).

§ J. S. Diller and T. W. Stanton, Bull. Geol. Soc. America, Vol. 5, 1894, p. 436.

the west (e.g. Ogden quartzite of Fortieth Parallel section) were laid down in the Eastern Belt. If the Western Belt were generally submerged beneath the sea during the Mississippian time, we should expect that few beds other than limestone and volcanics would be laid down in that belt, unless we postulate the contemporary existence of a large land-mass to furnish clastic material, necessarily situated on the present site of the eastern Pacific. The notably few suggestions as to the presence of pre-Cambrian terranes in the Western Geosynclinal Belt correspond to the difficulty of identifying them in a region which bears few or no traces of Cambrian sedimentation and but few of Ordovician Silurian, or Devonian sedimentation. At the same time, it is reasonably certain that pre-Cambrian rocks have been so deeply buried under the Carboniferous and later sediments and so much replaced by intrusive, batholithic material, that the areas of pre-Cambrian rocks can rarely be extensive in any part of the Western Belt. Much of the granite and gneissic rock mapped as belonging to the (Archean) Shuswap series of southern British Columbia, may be really intrusive and post-Carboniferous in age. No other large area of rocks in the Western Belt has been definitely referred to the pre-Cambrian.

The detailed discussion of these various correlations would itself fill a considerable volume and must be omitted in the present report. For further considerations the reader is referred to the works already noted.

As an aid to the understanding of the correlation from the viewpoint of physical geology, the preceding table has been recast in the form of Table XXXVI, in which the chief processes leading to the present composition and structure of the Western Geosynclinal Belt at the seven standard sections, are enumerated. A final summary is offered in the form of Table XXXVII, which is a composite of the seven columns of the last-mentioned table.

TABLE XXXV—*CORRELATIONS WITHIN THE WESTERN GEOSYNCLINAL BELT.*

—	Southeastern Alaska.	Western British Columbia and Yukon.	Western Geosynclinal Belt, 49th Parallel.	Central Washington.	Oregon and Northern California.	Middle California.
Pleistocene.	Gravels, sands, and clays. Glacial drift.	Alluvium. Glacial drift.	Alluvium. Glacial drift. Mt. Baker lavas. Basalt dikes cutting Cathedral granite.	Alluvium. Glacial drift. Most recent of Cascade Range lavas.	Alluvium and marine sands. Glacial drift. Basaltic flows.	Alluvium. Glacial drift. Basaltic flows.
Pliocene.	?	Horsefly gravels.	?	Some of Cascade Range lavas.	Tuscan tuff; pyroclastics.	?
Miocene.			Batholiths of granite, granodiorite and syenite; diorite stocks; Midway alkaline eruptives.	Some of Cascade Range lavas. Snoqualmie granodiorite and granite, batholith. Ellensburg formation; sandstone, conglomerate. Keechelus andesitic series. Yakima basalt. Guye formation: shale, sandstone, etc. Taneum andesite.	Empire formation of Oregon; sandstone, shale. Ione formation, Cal.; sand and shale.	River and shore gravels, auriferous gravels. Ione formation (Neocene).
Oligocene.	Kenai series; friable sandstones, conglomerates, shales and coal seams.	Upper Volcanic group. Tranquille beds. Lower Volcanic group. Coldwater group.	Older lavas, Midway Volcanic group. Kettle River formation. Skagit Volcanic formation (Eocene?)	Manastash formation; sandstone, conglomerate and shale.	?	?

TABLE XXXV—*CORRELATIONS WITHIN THE WESTERN GEOSYNCLINAL BELT.—Continued.*

—	Southeastern Alaska.	Western British Columbia and Yukon.	Western Geosynclinal Belt, 49th Parallel.	Central Washington.	Oregon and Northern California.	Middle California.
Eocene.	(Kenai series ?)	Puget group (in part).	Kruger alkaline intrusive body(?) Huntingdon formation; conglomerate, sandstone, shale and coal-beds.	Roslyn formation; sandstone, shale and coal. Teanaway basalt. Kachess rhyolite. Swauk formation; conglomerate, arkose, sandstone and shale. Puget group of coast.	Arago formation, Ore.; sandstone, shale and coal.	Tejon formation; sandstone and conglomerate.
		Unconformity.	*Unconformity.*	*Unconformity.*	*Unconformity.*	*Unconformity.*
Upper Cretaceous.	Sandstones, shales and coals (Kuiu Island). *Unconformity.*	Nanaimo group; conglomerates, shales and sandstones; some coal seams.	Pasayten series, upper part; shale and sandstone.		Chico formation; sandstone, shale and conglomerate.	Chico formation. *Unconformity.*
Lower Cretaceous.	Gravina series (Mesozoic ?); conglomerates and slates. Kasaan greenstone (Mesozoic ?); intrusives and extrusives.	Queen Charlotte group; conglomerates, sandstones, shales and agglomerates.	Pasayten series, lower part; sandstone, conglomerate, shale and breccia. Tamihy series (?); rocks like Pasayten series. Rossland volcanics in part?; Phœnix volcanic formation? (chiefly andesitic).		Shasta series: Horsetown formation; sandstone & shale. Knoxville formation; shale, sandstone. Myrtle formation, Ore.; conglomerate, sandstone and shale. Quartz-diorite stocks.	Granodiorite and granite batholiths (Jurassic ?) Diorite and gabbro stocks (Jurassic ?)
	Unconformity.	*Unconformity.*		*(See above.)*	*Unconformity.*	*(See above.)*

Jurassic.	Coast Range intrusives probably Jurassic); diorites, granodiorites and granites.	Coast Range intrusives (batholith); granodiorites, granites and diorites.	Granodiorite and granite stocks, and batholiths; diorite stocks.	Mt. Stuart grano diorite, batholith. Quartz-diorite stocks, Mt. Stuart area.	Potem formation; shale, sandstone, etc. Bagley andesite. Modin formation: sandstone, shale, etc.	Monte de Oro formation. Mariposa formation. Milton formation. Sailor Canyon formation. [These four formations mapped as Juratrias.]
					Unconformity.	*Unconformity.*
Triassic.		Vancouver series and Nicola group; volcanic material, with intercalated limestones and argillites.	Cultus formation; argillite and subordinate sandstone.		Brock shale. Hosselkuss limestone. Pit formation; shale, sandstone and tuff. Bully Hill rhyolite. Dekkas andesite.	*(See above.)*
	(See above.)	*Unconformity.*	*Unconformity probable.*		*Unconformity?*	*Local unconformity.*
Carboniferous.	Ketchikan series (probably in part Triassic); phyllites with some crystalline limestone and much greenstone.	Cache Creek group; slates or schist, cherty quartzites, volcanic material and interstratifide limestone.	Pend D'Oreille, Attwood, Anarchist, Hozomeen and Chilliwack series; argillite, phyllite, quartzite, limestone, chert, with much contemporaneous greenstone lava; associated basic and ultrabasic intrusives. (These series including also pre-Carboniferous?)	Peshastin formation; slate, chert, grit, limestone lenses. Hawkins formation; breccia, tuff, amygdaloid (closely associated with the Peshastin). Easton formation; mica-schist, hornblendeschist, epidote schist, amphibolite (pre-Carboniferous?)	(Pennsylvanian): Nosoni formation; tuff, conglomerate, shale, sandstone, limestone lenses. McCloud limestone, with chert nodules. (Mississippian): Baird formation; tuff, sandstone, shale. Bragdon formation; shale, sandstone, etc.	Robinson formation and Calaveras formation; argillite, limestone, quartzite, chert, mica schist, greenstone interbeds.
					Unconformity.	

TABLE XXXV—*CORRELATIONS WITHIN THE WESTERN GEOSYNCLINAL BELT.—Concluded.*

—	Southeastern Alaska.	Western British Columbia and Yukon.	Western Geosynclinal Belt, 49th Parallel.	Central Washington.	Oregon and Northern California.	Middle California.
Devonian.	Vallenar series (at least in part Devonian); blue limestones, calcareous and clay slates.	?	?	?	Kennet formation; shale, sandstone, limestone lenses. *Unconformity.* Balaklala rhyolite and Copley metaandesite (Devonian or older).	?
Silurian.	Wales series (probably in part at least, Silurian); crystalline limestones and slates.	?	?	?	?	Montgomery limestone.
Ordovician.	Graptolitic black shales found on Dean River, British Columbia.	?	?	?	?	?
Cambrian.	?	?	?	?	?	?
Pre-Cambrian.	?	Shuswap series; gneiss, mica-schists, lime-stones and quartites.	?	?		?

TABLE XXXVI.—*GEOLOGICAL EVENTS IN PROVINCES OF THE WESTERN GEOSYNCLINAL BELT.*

—	Southeastern Alaska.	Western British Columbia and Yukon.	Western Geosynclinal Belt, 49th Parallel.	Central Washington.	Oregon and Northern California.	Middle California.
Pleistocene.	Glaciation.	Glaciation.	Local vulcanism. Glaciation.	Local vulcanism. Glaciation.	Local vulcanism. Glaciation.	Local vulcanism. Glaciation.
Pliocene.		Fresh-water sedimentation.		Local vulcanism.	Local vulcanism.	Local vulcanism. Fresh-water sedimentation.
Miocene.		Vulcanism. Fresh-water sedimentation. Vulcanism.	Vulcanism. Batholithic intrusion.	Vulcanism. Batholithic intrusion. (Orogenic disturbance). Fresh-water sedimentation.	Coastal marine sedimentation. Fresh-water sedimentation.	Coastal marine sedimentation. Fresh-water sedimentation.
		Unconformity.	*Unconformity?*	*Unconformity.*	*Unconformity.*	*Unconformity.*
Oligocene.	Fresh-water and marine (?) sedimentation.	Fresh-water sedimentation.	Vulcanism. Fresh-water sedimentation.	Vulcanism? Fresh-water sedimentation.		
Eocene.	Fresh-water and marine (?) sedimentation.	Coastal marine sedimentation.	Coastal marine sedimentation.	Coastal marine sedimentation. Fresh-water sedimentation with vulcanism.	Coastal marine sedimentation.	
		Unconformity.	*Unconformity.*	*Unconformity.*	*Unconformity.*	

TABLE XXXVI—*GEOLOGICAL EVENTS IN PROVINCES OF THE WESTERN GEOSYNCLINAL BELT.—Con.*

—	Southeastern Alaska.	Western British Columbia and Yukon.	Western Geosynclinal Belt, 49th Parallel.	Central Washington.	Oregon and Northern California.	Middle California.
Upper Cretaceous.	Marine sedimentation with vulcanism.	Coastal marine sedimentation.	Local marine sedimentation.		Local marine sedimentation.	Local marine sedimentation.
	Unconformity.					*Unconformity.*
Lower Cretaceous.	Coastal marine sedimentation. Vulcanism?	Coastal marine sedimentation with vulcanism.	Local marine sedimentation. Vulcanism.		Local marine sedimentation.	Batholithic intrusion (Upper Jurassic?)
	Unconformity.	*Unconformity.*	*Unconformity.*	*(See above.)*	*Unconformity.*	*(See above.)*
Jurassic.	Batholithic intrusion.	Batholithic intrusion.	Batholithic intrusion.	Batholithic intrusion.	Batholithic intrusion (Lower Cretaceous?) Marine sedimentation, with vulcanism.	Marine sedimentation.
Triassic.		Marine sedimentation with vulcanism.	Marine sedimentation (general?)		Marine sedimentation, with vulcanism.	Marine sedimentation, with vulcanism.
	(See above.)	*Unconformity.*	*Unconformity probable.*		*Unconformity?*	*Local unconformity.*
Pennsylvanian.	Marine sedimentation with vulcanism.	Marine sedimentation with vulcanism.	Marine sedimentation general, with vulcanism	Marine sedimentation general, with vulcanism.	Marine sedimentation, with vulcanism.	Marine sedimentation, with vulcanism.

Mississippian.	?	?	?	?	Local marine sedimentation, with vulcanism.	Local marine sedimentation, with vulcanism.
					Unconformity.	
Devonian.	Local (?), coastal (?) marine sedimentation.				Local marine sedimentation, with vulcanism.	
Silurian.	Local (?) marine sedimentation.					Local marine sedimentation.
Ordovician.	Local (?) marine sedimentation.					
Cambrian.						
Pre-Cambrian.						

TABLE XXXVII.—PRINCIPAL EVENTS RECORDED IN THE WESTERN GEOSYNCLINAL BELT AS A WHOLE.

	Pleistocene	Local vulcanism. Glaciation.
	Pliocene	Local vulcanism. Fresh-water sedimentation.
		Local orogenic movement; local unconformity.
	Miocene	Local batholithic intrusion. Widespread vulcanism. Fresh-water sedimentation. Local marine sedimentation.
		Local orogenic movement; local unconformity.
	Oligocene	Local vulcanism. Fresh-water sedimentation.
LOCAL EOCENE GEOSYNCLINALS.	*Eocene*	Fresh-water sedimentation. Local vulcanism. Coastal marine sedimentation.
		General orogenic movements and widespread unconformity.
LOCAL CRETACEOUS GEOSYNCLINALS.	*Upper Cretaceous*	Local vulcanism. Coastal and other marine sedimentation.
		Local orogenic movements and local unconformity.
	Lower Cretaceous	Coastal and other local marine sedimentation. Local vulcanism. Local batholithic intrusion (Upper Jurassic ?)
		Widespread unconformity.
WIDESPREAD JURA-TRIAS GEOSYNCLINAL.	*Jurassic*	Widespread batholithic intrusion. Local vulcanism. Local (widespread ?) marine sedimentation.
		General orogenic movements (late Jurassic).
	Triassic	Widespread marine sedimentation (general ?). Relatively widespread vulcanism.
		Probably widespread though not energetic crustal movements and local unconformity.
GENERAL CARBONIFEROUS GEOSYNCLINAL.	*Pennsylvanian*	General marine sedimentation. Very widespread vulcanism (general ?).
		General subsidence in Western Geosynclinal Belt; simultaneous general uplift in Eastern Geosynclinal Belt except in its southern third.
	Mississippian	Local marine sedimentation. Local vulcanism.
		Local crustal movements and unconformity.
GENERAL EROSION IN WESTERN BELT, WITH FORMATION OF ROCKY MOUNTAIN GEOSYNCLINAL.	*Devonian*	Local marine sedimentation. Local vulcanism.
	Silurian	Local marine sedimentation. Local vulcanism.
	Ordovician	Local marine sedimentation.
	Cambrian	? General erosion.
	Beltian	? General erosion in later part.

GENERAL FEATURES OF THE WESTERN GEOSYNCLINAL BELT.

The various tables illustrate fairly well the safer generalizations which may now be made concerning the geological history of the Western Geosynclinal Belt.

1. The western one-third or two-fifths of the Cordillera forms a belt of great rock-formations which together constitute a single geological province. These formations are uniform in their very diversity as they are followed from south-eastern Alaska, or indeed, from northwestern Alaska, to middle and southern California.

2. It is equally clear that the Western Belt is in deep contrast with the Eastern Belt and that in a large way the two are in reciprocal relations. The area covered by the Western Belt has furnished most of the clastic material in the principal geosynclinal of the Eastern Belt; the Eastern Belt has furnished most of the clastic material composing the principal geosynclinal of the Western Belt.

3. The dominant sediments in the Western Belt seem undoubtedly to be the Upper Carboniferous, the Triassic, and, in less degree, the Jurassic. The Pennsylvanian beds seem to be absolutely continuous from southern California to Alaska and to have unusual thicknesses in all the more complete sections known. They and the locally underlying Mississippian as well as older beds compose the broad, fundamental prism of sediments out of which the post-Jurassic mountains were made. This whole older group of beds may be called for convenience, the Carboniferous Geosynclinal.

The generally conformable Jurassic-Triassic series, totalling great thicknesses, especially in California, has been proved at a few points to be unconformable upon the Pennsylvanian but the unconformity may not be very great. The rocks of all three systems are most intricately involved with one another and have shared in the paroxysmal movements of Jurassic and later time, as if they had all belonged to one conformable group. While, therefore, we may refer to the Jura-Trias beds under the name 'Jura-Trias Geosynclinal,' it will be convenient to have a name for the entire series of Carboniferous (and older?), Triassic, and Jurassic strata which have co-operated in the making of the larger sedimentary complex of the Western Belt of the Cordillera. The complex may be called the 'Main Pacific Geosynclinal.'

The enormously thick prisms of clastic deposits laid down in the Cretaceous are distinctly local and are separated by first-class unconformities from Jura-Trias-Carboniferous on the one hand, and Tertiary formations on the other. All of these prisms may be called Cretaceous geosynclinals and each may be given a geographical name, e.g., Pasayten geosynclinal, Shasta geosynclinal, Queen Charlotte geosynclinal, etc.

Similarly, the heavy Eocene deposits may be called the Puget geosynclinal, Arago geosynclinal, etc.

The stratified deposits of the other periods are not recorded to have sufficient thickness to warrant our recognizing true geosynclinals, i.e., bodies thick enough to control mountain-building and of dates other than Eocene, Cretaceous, and Carboniferous as now defined.

4. The Western Belt is a unit as regards the evidences of its behaviour during mountain-building periods. The general orogenic periods include at least the late Jurassic and the post-Laramie. In each case the degree of deformation and metamorphism is comparable in all sections where detailed studies have been made.

The more local, late Miocene, late Oligocene, mid-Cretaceous, and pre-Triassic crustal movements were also respectively of the same order whether recognized in Alaska, British Columbia, or the American States.

5. The western Belt is specially distinguished from the eastern Belt by the extraordinary repetition, in the former belt, of heavy vulcanism in all thirteen of the periods noted in the tables. Volcanic rocks are far from common in the Eastern Belt and have everywhere but limited range.

6. Finally, the Western Belt is to be considered a geological unit also because of the steady relation of bedded rocks and batholiths from end to end of the long mountain-chain. The late Jurassic invasion of the roots of the mountains was almost as general a phenomenon as the post-Jurassic unconformity or the late Carboniferous sedimentation. The proved late Miocene intrusion of batholiths is more local, but future studies will doubtless increase the number of exposed granites which are referable to the Tertiary.

Batholithic intrusion is known in the Idaho portion of the Eastern Geosynclinal Belt, and elsewhere has afforded bodies of huge size, but post-Cambrian batholiths are comparatively rare in that belt. This contrast of the two belts is partly to be related to the higher degree of orogenic crumpling, overthrusting, and overfolding in the Western Belt as compared with the slighter disturbances of the stronger rocks of the Eastern Belt. Yet the fact that, through the entire width of the Cordillera, mountain-building has been controlled by thrust from the Pacific basin is obviously of prime importance in this connection.

The comparison of the two great belts into which the North American Cordillera may be divided results in the view that the Cordilleran axes of geosynclinal warpings and of orogenic foldings have remained largely parallel from late pre-Cambrian time to the present. Obvious as may be the contrast of the two belts in their respective complex histories, the interpretation of that contrast needs the steady attention of geologists for generations to come. It would be out of place to attempt here a full discussion of the subject. It has been touched upon rather to prepare the way for the following brief account of the history of the Cordillera at the Forty-ninth Parallel. This legitimate field for the present report could not be wisely entered without a preliminary survey of the vast mountain-unit through which the International Boundary runs. Since this has been the express purpose of the foregoing correlations, they have not been treated in the full way their importance demands.

CHAPTER XX.

SUMMARY OF GEOLOGICAL HISTORY AND NOTE ON OROGENIC THEORY.

Geological History of the Cordillera at the Forty-ninth Parallel.

1. The earliest event recorded in the rocks exposed in the Boundary belt is the important pre-Cambrian sedimentation leading to the formation of the Priest River terrane. The exposures offer no hint as to the position of the lands whence the clastic materials represented in this terrane were derived. On account of the fine grain of the clastic rocks we are entitled to believe that the lands were distant. The nature of the beds shows that the land mass or masses were composed of granitic or gneissic rocks, that is, the usual abundant types which carry much free quartz as well as alkaline feldspar. The degeneration and erosion of either granite or gneiss would give just such deposits on the ancient sea-floor as would correspond to the heavy quartzites, quartz schists, metargillite, and mica schists now exposed as the dominant types in the terrane. The sedimentation was doubtless marine, as there are thick dolomites interbedded with the silicious beds at many horizons. The composition and genesis of the Priest River terrane have many analogies to those of the Huronian formations of the Great Lakes district. Leading differences are, however, found in the apparent absence of contemporaneous volcanics, true cherts, jaspilites, and iron-ore in the western area.

2. The Priest River rocks were thoroughly consolidated, probably mountain-built and somewhat metamorphosed before pebbles were yielded to the Irene conglomerate.

3. In the Eastern Geosynclinal Belt the period covering the deposition of the Irene conglomerate and the Mississippian limestone inclusive, was occupied in the formation of the Rocky Mountain Geosynclinal, the principal lithological feature of the Eastern Geosynclinal Belt. The clastic sediments forming this huge unit were derived from a western land composed of the Priest River terrane and of granitic or gneissic masses perhaps identical in age and composition with those whence the materials of the Priest River quartzites had been formed through yet older weathering. Throughout this long period of more or less continuous downwarping it is evident that the western shore-line of the geosynclinal area must have shifted considerably. The probabilities are, however, that for most of the period, they were located in a comparatively narrow, meridional zone. This zone seems to have been located near the longitude of the Columbia river. To west of this zone there must have been a wide belt of land stretching far to the north and south of the Forty-ninth Parallel. That

land may have had a width approximating that of the Cordilleran division here recognized as the Western Geosynclinal Belt.

The Rocky Mountain Geosyncline was doubtless limited, also on the east, by definite shore-lines like those proved to have existed in the Belt mountains not far south of the International Boundary.

On both sides of the geosyncline there were specially important transgressions of the sea during the Middle Cambrian (Flathead), and the Mississippian periods. At those times the downwarped area was notably widened but in neither case did it lose its character of a geosyncline with north-northwest and south-southeast axis.

In the geosynclinal area contemporary vulcanism interrupted the deposition of clastic or chemical sediments at several different periods. The first volcanic activity broke out soon after the initiation of the downwarp, developing the Irene Volcanic formation. Less important eruptions occurred during the deposition of the Grinnell, Sheppard, and Kintla formations, while the singularly persistent Purcell Lava was poured out at the close of the Siyeh stage. It is probable that this last lava is contemporaneous with the thick sills of gabbro which have been thrust into the bedding-planes of the quartzites in the Purcell mountain system.

4. Up to this time we have no record except that of steady erosion for the Western Cordilleran Belt east of the Gulf of Georgia. The great volume of the Rocky Mountain Geosynclinal implies that the western land-area was steadily or spasmodically rising during this deposition of clastic material on the east. It is quite possible that during the Mississippian period, the already heavily eroded land of the Western Belt was temporarily submerged and received a marine sedimentary veneer; but of this we have no paleontological evidence on or near the Forty-ninth Parallel.

It is also possible that some of the oldest greenstones of the Columbia mountain system and of the Interior Plateaus region are of pre-Pennsylvanian dates, representing vulcanism on the land-surface of the Western Belt.

5. At or near the close of the Mississippian period the Western Cordilleran Belt was certainly submerged, and the Eastern Geosynclinal Belt was broadly upwarped, without other *general* deformation of the Rocky Mountain Geosynclinal. The Main Pacific Geosyncline was thus initiated or else deepened, so as to receive a great load of Pennsylvanian sediments. Fossiliferous beds belonging to this period have been found at intervals in the Western Belt from the Columbia river to Vancouver island. So far as they are clastic their materials seem to have been derived from the newly emerged Eastern Belt. The ancient relation of the two belts was thus reversed, except for local, temporary embayments on the east. This movement was, apparently, felt from Alaska to northern Utah at least; farther south, in the region of the Fortieth Parallel, the reversal of relations was postponed to the close of the Pennsylvanian period. Otherwise the Eastern and Western Belts have respectively behaved as units in the momentous change. The larger part of the Eastern Belt was to remain as land through the Permian, Triassic, and most of the Jurassic periods; and even in the later periods to undergo only partial submergence.

The new relation between the two Cordilleran belts was so similar to that which obtained on the line of the Fortieth Parallel at the close of the Upper Carboniferous period, that it is instructive to review King's statement, published on pages 536-7 of the volume on Systematic Geology, Fortieth Parallel Survey:—

> 'After the close of this great conformable Palæozoic deposition, widespread mechanical disturbance occurred, by which the land-area west of the Nevada Palæozoic shore became depressed, while all the thickest part of the Palæozoic deposits from the Nevada shore eastward to and including the Wahsatch, rose above the ocean and became a land-area. Between the new continent and the old one which went down to the west, there was a complete change of condition. The land became ocean; the ocean became land. . . .
>
> 'Upon the western side of the new land-mass, the Archæan continent, having gone down, made a new ocean-bottom, and upon this immediately began to accumulate all the disintegration-products of the new land-mass which the westward draining rivers and the ocean waves were able to deliver. Throughout the Triassic and Jurassic periods the western ocean was accumulating its enormously thick group of conformable sediments upon the Archæan floor, . . until, at the close of the Jurassic age, there had accumulated in the western sea 20,000 feet . . of Triassic and Jurassic material.'

6. During the Pennsylvanian period the Main Pacific Geosyncline was the scene of heavy sedimentation with accompanying powerful vulcanism. The rock exposures at the Forty-ninth Parallel do not suffice to show clearly the dynamic events leading to the Triassic, but from Dawson's work in Vancouver island as well as on the mainland, it appears that there was local deformation of the Pennsylvanian beds in that part of the Cordillera, followed by erosion of the upturned strata, before these were buried beneath Triassic deposits. It is likely that the same crustal movement affected the Forty-ninth Parallel section; and, further, that it is to be correlated with the beginning of the Sierra Nevada downwarp described, as above, by King. How long or how extensive was this temporary return to land conditions in the Western Belt cannot be declared. It is known, however, that the Triassic period saw, at the Forty-ninth Parallel, a resumption of marine sedimentation on the Pacific side of the belt. Argillites, sandstones, and limestones, together with great piles of basic volcanic material were then laid upon the Pennsylvanian formations in this region.

7. The rocky record is blank for most of the Jurassic period, probably indicating that an upheaval of the Triassic sea-bottom had begun, as an early preparation for the late Jurassic revolution. This is the first general orogenic revolution affecting the Western Cordilleran Belt since the Pre-Cambrian. It was immediately followed by the intrusion of many large batholiths of granodiorite and allied rocks. Many of the larger batholiths between the Purcell Trench and the open Pacific Ocean were intruded at this time.

8. The Eastern Geosynclinal Belt was little affected by these great crustal and subcrustal movements in the west. Its Paleozoic beds still lay widely flat, with their surface probably but little above the sea through the whole of the lower Mesozoic. The Jurassic revolution of the west had no more affected these strong rocks than the Alleghany plateau region was affected by the force which set the strata of Virginia and Pennsylvania writhing into sharp folds at the close of the Paleozoic. At the very close of the Jurassic there was, apparently, a slight submergence of the eastern edge of the Eastern Cordilleran Belt beneath the mediterranean waters of North America; perhaps this slight movement was an echo of the strife of force and matter along the Pacific.

9. Extremely rapid erosion of the new Jurassic mountains in the west uncovered some of the granitic batholiths, thus removing thousands of cubic miles of rock from these mountains. Some of the clastic material was, during the Cretaceous (Shasta-Chico) period deposited in local geosynclines formed on the Jurassic granites or on older formations. Local vulcanism initiated the downwarp in at least the one case of the Pasayten Cretaceous geosyncline. Besides the 1,400 feet of pyroclastics thus formed, some 29,000 feet of sandstone, conglomerate and shale were deposited in this one downwarp.

10. While the Pasayten, Queen Charlotte, and other of these local geosynclinals were forming in the Western Belt, the Eastern Belt was similarly affected by downwarps and the formation of sedimentary prisms of geosynclinal thickness. The nearest demonstrated geosynclinal belonging to this period is that in the Crowsnest district, but further study may show that the Cretaceous beds attained a thickness of over 6,000 feet at the Forty-ninth Parallel itself.

Meanwhile the eastern half of the Western Cordilleran Belt and the western half of the Eastern Cordilleran Belt formed a broad and fairly continuous area of land; from it the geosynclinals to east and west were fed with detritus. The central land-mass seems to have been locally the scene of heavy volcanic action, typified by the younger basic effusives in the Rossland district. The reader will remember, however, that the dating of this particular part of the Rossland volcanic group is very uncertain; perhaps it should be referred to the Jurassic or even the Triassic.

11. When the larger Cretaceous geosynclinals reached critical depths, the post-Laramie or 'Laramide' revolution took place. The structural turmoil of the already crumpled Paleozoic and Triassic rocks in the Western Geosynclinal Belt was greatly enhanced. A deformation almost as intense was simultaneously produced in the Eastern Geosynclinal Belt. The gigantic overthrusts and horizontal shifts, so marked in the Selkirk, Purcell, Clarke, and Lewis ranges, were probably then caused, although Willis notes the alternative possibility that the Lewis thrust dates from the mid-Tertiary. Much of the normal faulting characteristic of the Purcell and other ranges is most likely to have been produced in the late stage of the Laramide revolution.

12. So great an orogenic revolution, the only *general* occurrence of the kind in the whole Cordillera in these latitudes since the pre-Cambrian, might be

expected to have preceded batholithic intrusion. So far, however, no Eocene granites have been demonstrated. With doubt the intrusion of the Kruger alkaline body in Kruger mountain has been referred to that period.

13. The new, very strong topography produced by this Laramide upturning seems not to have permitted important sedimentation in the area of the Boundary belt. A hundred miles to the south very thick prisms of fresh-water beds were laid down in the State of Washington. The Tertiary formation of Sumas mountain was probably part of the once continuous body of clastic material carried into the Eocene geosynclinal of Puget Sound and the Gulf of Georgia. This sedimentation was the reciprocal of extensive and profound denudation in the Belt of Interior Plateaus. During the Eocene the Eastern Geosynclinal Belt was, at the Forty-ninth Parallel, eroded apparently through its whole width.

14. Judging by analogies from adjacent regions north and south, the Puget Eocene geosynclinal area was, at the close of the Eocene proper, uplifted though not strongly deformed.

15. The Oligocene continued the erosive work of the Eocene over most of each of the great Cordilleran belts. West of Midway, some of the detritus was trapped during the sway of the local vulcanism, with the production of a notable fresh-water series of sandstones, argillites, and conglomerates (Kettle River formation).

16. The early Miocene was also a time of general erosion all across the Cordillera; only very limited fresh-water deposits were made. On the Forty-ninth Parallel the only one referable to this date is that flooring the fault-trough at the North fork of the Flathead river.

17. Toward the close of the Miocene, the Oligocene fresh-water beds at Midway were moderately upturned and eruptions of rhomb-porphyry, 'shackanite,' trachyte, and pulaskite porphyry overwhelmed the older Midway lavas and the Kettle River sediments. Probably at this time also the Eocene beds of Sumas mountain far to the west were somewhat tilted and faulted; and the more yielding Miocene clays and sandstone of the Flathead trough were strongly deformed. It is possible that the Cretaceous rocks of the Pasayten district were further disturbed, though we must ascribe their principal deformation to the much more powerful crustal adjustments of the Laramide revolution.

18. The Miocene deformation was closely followed by new extensive, batholithic intrusions. These seem to be registered in the great Similkameen and Cathedral batholiths in the Okanagan range; the Castle Peak stock of the Hozomeen range; the Coryell syenite batholith and its satellites of the Rossland mountains; and the large Bayonne batholith and its satellites of the Selkirks. As abundantly indicated in the foregoing chapters, these correlations are provisional only, and a date so recent for these great intrusive bodies is not proved for any one of them. There can, however, be little doubt that all of them are of post-Cretaceous age, following the Laramide revolution.

19. The strength of the Cordilleran topography was doubtless considerably increased by these late Miocene movements. Since then, both of its geosynclinal belts have suffered steady erosion by river and glacier. The Pliocene

leaves no sedimentary record on or near the Forty-ninth Parallel except, it may be, the Kennedy gravels described by Willis as a subaerial apron of gravel flung out on the plains from the eastern foot of the Lewis range. At the Forty-ninth Parallel there are no known criteria whereby it can be shown that this part of the Cordillera suffered massive warping such as that supposed to have affected the Cascades in Central Washington during the Pliocene.

20. One of the last important changes in the constitution of the region adjoining the Boundary belt is the growth of Mt. Baker, a volcano perhaps begun in the Pliocene and continuing its activity through the Pleistocene and Recent periods.

21. Finally, it should be remarked that the later history of the Cordillera is to be read largely and, for great areas almost solely, as a result of detailed physiographic studies. These should be as far as possible quantitative and must cover a much wider zone of the Cordillera than that surveyed along the International Boundary. Therefore, in the latest, as in the earliest, and all the middle chapters of the history here outlined, much remains to be done before this part of the mountain-chain is genetically understood.

Observations bearing on the Theory of Mountain Building.

The conditions affecting the origin of mountain ranges have long been recognized as offering some of the toughest problems in geology. The difficulties of the old contraction theory seem to be enhanced by the discovery that a notable part of the earth's surface heat is due to radioactivity. Assumptions as to the earth's original temperatures, either in the thin surface shell or crust or in the vast interior, can not now be made with the relative degree of confidence felt by some writers before the radioactivity of nearly all accessible rock-matter was demonstrated. Further complications have recently been introduced by the launching of the planetesimal hypothesis, which has not been developed sufficiently, so that the earth-shell bearing the maximum heat of compression can be located or the thermal state of the earth during geological time described. A stable orogenic theory founded on thermal contraction involves also a suitable cosmogonic theory of the earth. It is safe to conclude that it will be long before there can be unanimous opinion on the validity of the contraction hypothesis of mountain-building. Other explanations are but fragmentary and they likewise suffer from our lack of information as to the exact thermal condition of the earth's interior.

The study of the Forty-ninth Parallel section has led to few novelties in theoretical suggestions on this subject but it has found many new illustrations of recognized orogenic principles. Among the significant facts are the following.—

1. At the Forty-ninth Parallel, as generally throughout the North American Cordillera, each period of orogenic folding has been preceded by heavy sedimentation. Each of the principal folded tracts is located within a geosynclinal belt.

2. Orogenic axes are generally parallel to the respective axes of the genetically connected geosynclinal prisms.

3. Each geosynclinal prism bears contemporaneous lavas, usually basaltic or andesitic. This rule is so persistent, in the Cordillera and elsewhere in the world, that we may believe there is some genetic relation between the downwarping and movements of the magmatic stratum beneath the earth's crust.

4. Granitic intrusion of the batholithic order, to observed levels, always follows periods of the more intense orogenic movement. This implies that the greatest abyssal injections of the earth's crust by magma are genetically associated with the horizontal shearing of a superficial earth-shell which is much thinner than the whole crust.

5. The topographic and structural effects of mountain-building at the Forty-ninth Parallel are clearly related to the degree of lithifaction (static metamorphism) undergone by the geosynclinal sediments. A leading illustration is seen in the prevalence of overthrusts, horizontal shifts, and fault-blocks in the strong Beltian-Cambrian terrane of the Eastern Belt, while close folding and mashing are features of the less consolidated, though otherwise petrographically similar rocks of post-Mississippian age in the Western Belt.

6. Yet, part of this contrast between the two belts is to be referred to the fact that orogenic pressure has been applied with greatest intensity on the Pacific (ocean) side of the Cordillera.

Toward the close of field work on the Boundary section, the writer attempted to relate these field conclusions to the prevailing contraction theory. The result was to hazard a speculation on 'Abyssal Igneous Injection as a Causal Condition and as an Effect of Mountain-building.'* The original summary of that paper may here be quoted.

The assumptions on which the hypothesis have been based are the following:—

(*a*) A cooling earth superficially composed of a relatively thin crust overlying a fluid gabbro (basaltic) substratum of unknown thickness.

(*b*) The substratum so much compressed by the weight of the crust as to be probably able to float the crust.

(*c*) Through differential cooling contraction the development of a level of no strain in the crust probably not much more than six miles below the earth's surface.

(*d*) The accumulation of pressure in the shell of compression and the simultaneous accumulation of cooling cracks and of some of the powerful tension unrelieved in the shell below the level of zero strain.

(*e*) A steady or recurrent dislocation in the shell of tension permitting of the forceful injection of the fluid substratum, to which even the viscous layer of the shell acts as a relatively solid mass at the moment of dislocation. This dislocation has been referred to the tidal torsion of the earth's crust, but subequatorial torsion on the tetrahedral theory of the earth, or crustal deforma-

* R. A. Daly, Amer. Jour. Science, Vol. 22, 1906, p. 195.

tion due to the play of other cosmical forces or of forces induced by the heterogeneity of the crust, may similarly cause dislocation in the shell of tension.

The conclusions may be similarly summarized:—

1. The abyssal injection involves condensation of the matter in the shell of tension. Cracks are closed and much of the accumulated tension is relieved by an enforced creep of matter away from the injected body. So long as the body remains fluid the stretching of this shell due to continued cooling of the earth is accomplished by creep of matter in the same directions. The amount of creep is at a maximum above the zone of injection and decreases to a minimum at certain distances to right and left of the middle line of the zone.

2. This lateral creep induces a down-warp of the earth's surface immediately overlying the zone of condensation. The resulting geosynclinal may be the seat of prolonged sedimentation. If so, the weight of the sediment itself tends to increase the lateral creep in the shell of tension and the down-warp slowly deepens.

3. The shell of compression is already weakened at the angles of down-warp; it is further weakened by the sedimentary blanket which, comparatively little resistant itself, causes a softening of its basement through a rising of the isogeotherms.* When the filling of the geosynclinal has sufficiently thickened, the shell of compression, owing to its secular accumulation of stresses (which are intensified by metasomatic changes in the shell), begins to collapse. Mountainous forms and structures result.

4. The complete shearing apart of the shells of compression and tension during the orogenic revolution releases the tensions still unrelieved in the underlying shell. Abyssal injection on a large scale is thus initiated or continued in the shell of tension. The relief of compressive stresses in the act of building the mountains first occasions the possibility of magmatic stoping and thus of the extensive assimilation of gneisses, schists, and sediments by the primary, basaltic magma. The differentiation of the compound magmas of assimilation may explain the batholithic central granites of mountain ranges, along with their satellitic stocks, injected bodies, and volcanic outflows.

5. The regional warpings of the earth's crust may be partly at least referred to the varying strengths of abyssal injections from a fluid substratum.

6. The location and alignment of mountain ranges, the location and elongation of geosynclinals, the final development of igneous batholiths and satellitic injections, are all interdependent and related to *special* zones of powerful abyssal injections from the substratum. These zones are, in the large, located by cosmical stresses affecting the earth along special azimuthal lines.

7. Mountain building causes relief of compressive stresses in the superficial shell. The surface outflow of magma, either secondary or directly derived from the substratum, may therefore be specially pronounced after an orogenic revolution. In general, the theory of vulcanism is also fundamentally affected by the doctrine of the shell of tensions which are not entirely relieved by the compressive extension of that shell.

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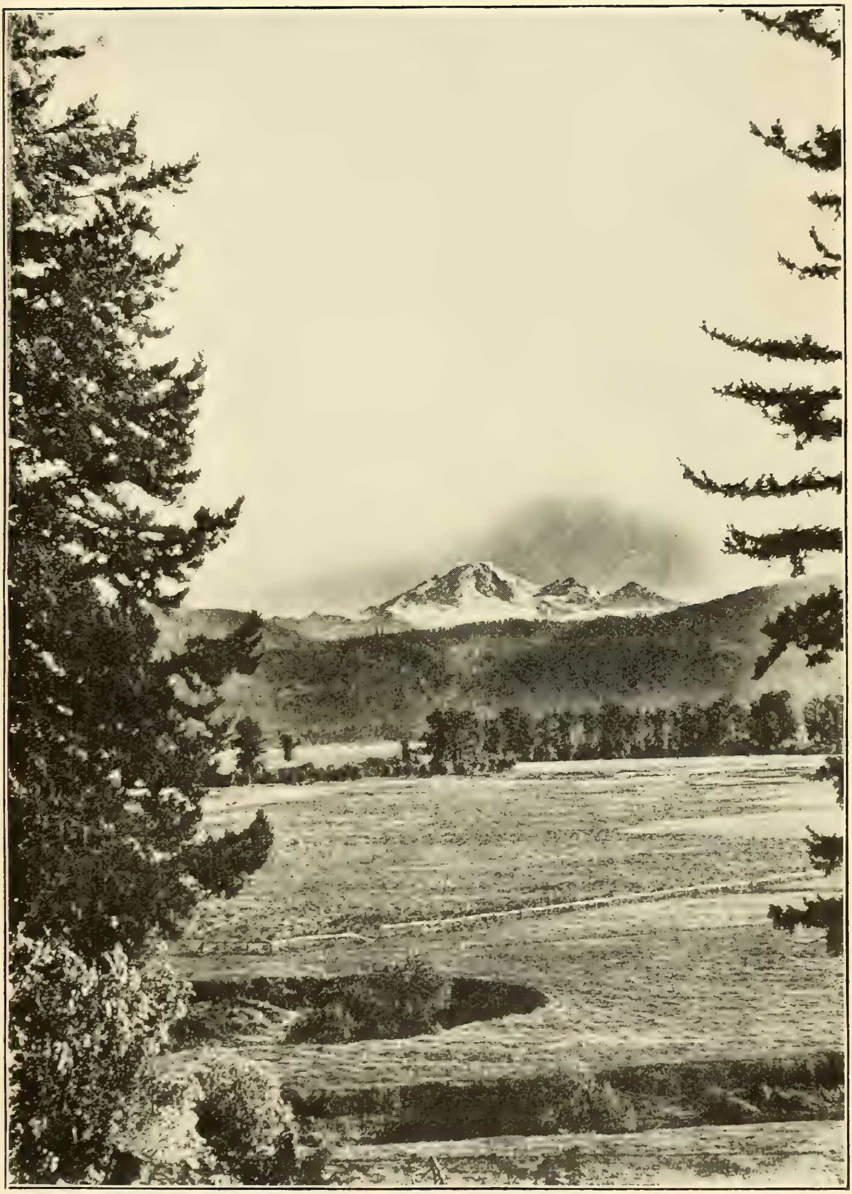
*Perhaps much of the heat thus locally conducted is of radioactive origin.



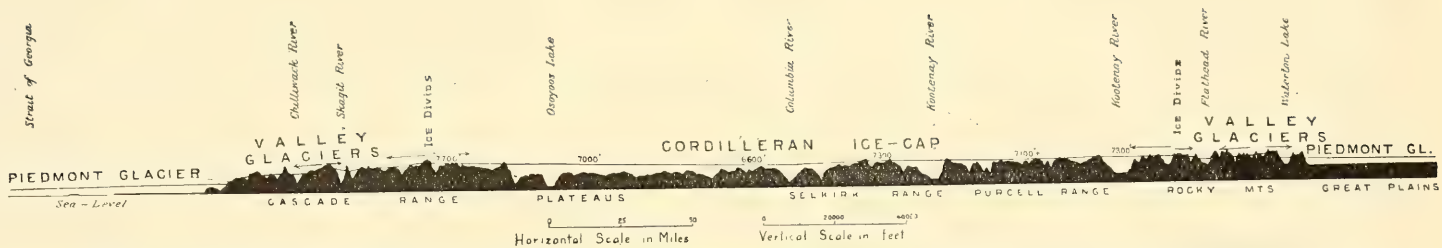
Mount Baker, taken from prairie at Sumas Lake, Fraser Valley.

The second part of postulate *d* is, perhaps, the most doubtful point in the speculation. Until more is known of the behaviour of silicate rocks at very high pressures, it is impossible to say how much cooling tension is left unrelieved by 'compressive extension' at the end of the period in which conditions have been ripened for mountain-building. However this may be, we must believe in abyssal injection as a fact. The concentration of igneous eruptions in special belts on the earth is also an evident fact. The view that repeated abyssal injections within such a belt must lead to a down-warping of the surface is a reasonable deduction, if the earth is cooling.

The speculative element enters when a downwarp of geosynclinal proportions is considered as an effect of this magmatic movement within and beneath the earth's crust. So far as it goes, the observation that vulcanism is always or almost always contemporary with geosynclinal sedimentation, tends to strengthen that belief. In each case the number of extrusions of lava at the surface may be but a small fraction of the number of abyssal injections within the limits of the geosynclinal belt. It is not an extravagant assumption to hold that the total volume of magma thus transferred into and through the crust may be comparable to the volume of the sedimentary prism. In spite of all the difficulties, the most satisfactory explanation for the origin and localization of the great downwarps seems to be found in movements of rock-magma under cosmical stresses. If this conclusion were proved, we should have gone far towards solving the orogenic problem, for the mystery of a mountain-chain lies no more in the folding of strata than in the development of the preliminary stratified prism.

That strong mountain-building disturbs the equilibrium of the magmatic substratum and initiates granitic intrusion is already sufficiently clear. In the following theoretical chapters on igneous rocks, evidence will be found for the belief that visible batholiths are the roof portions of huge basaltic injections chemically modified by assimilation of the injected formations. That belief rests on much more than mere speculation. The question arises as to whether these large-scale injections have also been facilitated by the condensation of the shell of tension. The answer given in the special paper is designedly speculative and the postulated mechanics may be faulty, but its central theme is strong; namely, that at its closing stage as well as in the formation of the preliminary geosynclinal, an orogenic movement is closely associated with the intrusion of magma into the earth's crust. The writer is inclined to the view that this association is close because it is genetic; and that investigators in orogeny have hitherto given too little attention to the relation of subcrustal, magmatic readjustments to mountain-building.

PLATE 49.



Profile cross-section of the Cordillera at the Forty-ninth Parallel, showing vertical limits of Pleistocene glaciation and the relation between the ice-cap and the flanking valley glaciers. Arrows show the direction of ice-movement during maximum glaciation.

CHAPTER XXI.

GLACIATION OF THE CORDILLERA AT THE FORTY-NINTH PARALLEL.

Introduction.

While collecting the data on the problems of bed-rock geology the writer attempted to note the leading observations which could be made on the Pleistocene glaciation of the Boundary belt. The results lack much in completeness, but they have the value of corroborating the general views of Dawson and other pioneer geologists who have traversed this part of the mountain chain. The study has further indicated how great a field is awaiting the detailed attention of glacial experts. The results of the writer's reconnaissance along the transmontane section will be summarized in the present chapter. Meagre as they are in certain respects, they have been achieved only after hundreds of more or less arduous climbs had been made; it is thought that a quantitative statement of the principal facts may be of some service to the students of the vast glaciated tract of the Cordillera.

A preliminary understanding of the principal conclusions concerning the distribution of the Pleistocene ice-fields can be attained by a glance at the diagrammatic section of Plate 49. It will be observed that the section shows a high degree of symmetry. The middle part of the Cordillera, 300 miles in width, was covered by a continuous ice-cap. To east and to west of this cap the Rocky Mountain system and Cascade mountain system were respectively covered by three sets of valley glaciers.

The eastern slope of the Clarke range shed ice-streams to the piedmont sheet at the Great Plains. The western slope of that range and the eastern slope of the MacDonald range shed valley glaciers to the main, south-flowing trunk glacier in the Flathead valley. The eastern ice-shed of the central ice-cap was located on the high ridges of the MacDonald range.

Similarly, the western slope of the Skagit range shed many valley glaciers to the piedmont sheet of the Gulf of Georgia, while the eastern slope and the Hozomeen range fed the local sheets which met and were drained away southward, down the Skagit valley.

A few nunataks projected above the ice-cap. In general the erosion of this colossal sheet tended to soften the contours of the overridden mountains, rounding off the corners, much as the sharp peaks and angles of the Greenland and Labrador coasts have been affected by the eastern ice-caps. In the belts of valley-glaciers, on the other hand, glacial erosion has greatly sharpened the mountain summits and ridges. This latter effect has been due chiefly to head-wall recession of the upper ends of the local glaciers. The amphitheatres or cirques, which are related products, will receive some illustration, and certain points in the theory of their formation will be discussed. Other cirques were developed in the area of the ice-cap, either about the projecting nunataks, or, and more generally, during the later time when the ice-cap, through climatic wastage, had become broken up into local areas of snow-field and valley glaciers.

Special attention was paid by the writer to the determination of the upper limits of the ice-sheets in the different ranges. The familiar criteria were used, and, for each glacial province, gave accordant results. The position and origin of high-level erratics, the extent of glacial polishing and grooving, the directions of striae on the higher peaks and ridge,—in general, the distinguishing of regional from local glaciation, were the natural points to be observed in mapping the limits of the ice-cap in altitude and in longitude. The errors in altitude are in most cases believed not to exceed one hundred or two hundred feet. In certain cases the striae did not give sure evidence as to the direction in which the ice had moved. In such cases lunoid furrows could sometimes decide the question, the direction of movement being always in the sense of the furrow's convexity. It may be noted in passing that lunoid furrows are relatively rare on the Cordilleran ledges as compared with the multitudes which may be seen along the Labrador coast. The reason for this contrast in the two heavily glaciated regions is not apparent.

The glacial deposits are as a rule of quite normal composition but rarely show systematic types of form. A few such forms will, however, be noted in describing the great master valleys, which in Glacial times were occupied by huge trunk glaciers either independent of, or inherited from, the central ice-cap.

The curious relation of the Rocky Mountain piedmont glaciers to the Keewatin ice-cap was not directly studied. For information relating thereto the reader is referred to Dawson's glacial papers* and to Calhoun's more recent paper on 'The Mountain Lobe of the Keewatin Ice Sheet'†

In what follows it will be seen how closely the writer's results accord with the general conclusions arrived at by Dawson.‡

The central ice-cap broke up into several wide lobes at no great distances south of the Forty-ninth Parallel. Within the Boundary belt no indication that there was more than one Glacial epoch in the Pleistocene was found in any one of the six field-seasons devoted to the section. All observed drift had the same freshness as that laid down in the later Wisconsin epoch of eastern glaciation.

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* Especially that in the Report of Progress, Geol. Surv. of Canada, 1882-4, Pt. C, p. 139.

† F. H. H. Calhoun, Prof. Paper, No. 50, U.S. Geol. Surv., 1906.

‡ See G. M. Dawson, Trans. Roy. Soc., Canada, Vol. 9, 1891, p. 3.

PLATE 50.

Glaciated valley of Starvation Creek, Clarke Range. Local moraine and Flathead Valley in distance.

Clarke Range.

During the Glacial period the Clarke range formed a strong divide between two sets of local glaciers. The eastern set headed in a multitude of cirques which were connected by a more or less continuous snow-field covering the slopes just east of the present 'Great Divide.' Some of these valley-glaciers descended to the wide trough now occupied by Waterton lake where the various sheets coalesced with others from the Lewis range, to form a broad north-flowing intermont glacier. Other glaciers moved down the Clarke range canyons directly to the Great Plains and there, with the wide Waterton glacier, formed part of the eastern piedmont ice-sheet of the Cordillera.

The western set of local sheets in the Clarke range descended their high-grade valleys and merged into the wide intermont glacier which largely filled the valley of the existing North Fork of the Flathead river. (Plates 50 and 12). This great sheet may be shortly referred to as the North Flathead glacier.

The writer has made no special study of the areas occupied by the Waterton glacier and eastern piedmont glacier. It is of interest, therefore, to note the conclusion of Calhoun that the Waterton, Belly River, and Lees Creek glaciers were probably confluent in one large piedmont sheet.

The main or upper Waterton lake doubtless owes its origin to the activities of the Waterton glacier. How far the basin is due to glacial excavation and how far to morainal damming cannot with certainty yet be declared. That the pre-Glacial valley has been considerably widened and deepened through glacial erosion is shown by the fact that Oil Creek 'hangs' at least 200 feet above the rock floor of Waterton lake. This break in the stream gradient is best explained as due to the more rapid glacial erosion of the main valley-floor as compared with the degradation of Oil Creek valley by its own, much smaller glacier. The relation suggests that the main Waterton lake in large part occupies a true rock-basin excavated by the powerful Waterton glacier.

The original Waterton lake has been divided into three unequal parts; the middle and lower lakes have been separated from each other and from the main lake by the growth of the post-Glacial deltas of Pass creek, eastward from the Clarke range, and of Coal creek westward from the Lewis range.

The erosive power of the Pleistocene high-level valley glaciers of the Rocky Mountains is wonderfully illustrated throughout the whole system from the Missouri river to Yukon territory. Thousands of shallow pre-Glacial valleys have been greatly deepened, their walls steepened, with the generation of abundant U-shaped cross-sections. Thousands of the valley-heads have been modified into typical cirques or amphitheatres, many of which are floored with small rock-rimmed lakes or tarns, those 'gems of the mountains.' The finest examples of these glacial effects occurring on and near the Forty-ninth Parallel are to be found in the Clarke and Lewis ranges. Probably nowhere in North America have cirques and glacial troughs been more tellingly mapped than in the Chief Mountain quadrangle of the United States Geological Survey Topographic Atlas. We owe this sheet to Matthes and Sargent, whose unusual accuracy and rare artistic skill have portrayed the topography of some 800 square miles. The quadrangle is bounded on the north by the Forty-ninth Parallel and includes part of each mountain range. Considerably more than one hundred cirques, about sixty mountain-tarns, and scores of typical, U-shaped glacial troughs are shown in this one sheet. The vast precipices, horns, and knife-edge ridges which dominate the magnificent scenery of the Rockies are faithfully represented. For all of these features there can be no question as to glacial origin. The glacierlets of the present day are, on a small scale, continuing the work of the hundreds of heavy ice-sheets which like double batteries, assailed the eastern and western slopes of each mountain range.

The drastic change in topographic quality induced by the erosion of the cirque glaciers is well illustrated in the photograph of Plate 51. This is a view of an 8,100-foot summit situated one mile northwest of the Boundary monument at the Great Divide in the Clarke range. The smooth, domical slope covered with a fine-textured felsenmeer of Kintla argillite represents a type of pre-Glacial slope. The nearly vertical head-wall of the cirque represents the quarrying of a small, north-flowing glacier. From the summit to the tarn at the bottom of the cirque is a drop of 1,500 feet. At least two-thirds of that depth is due to the erosion of one of the smallest of these Pleistocene valley glaciers.*

The 'over-steepening' of slopes and the development of fiord-like profiles are illustrated in Plates 7, 50 and 72, A. Where a pre-Glacial ridge suffered attack by glaciers on both slopes a razor-back form was often produced. A continuance of this double head-wall attack led to the isolation of sharp peaks or horns, like Mt. Thompson and its neighbours (Plate 9).

Nature and Extent of Glacial Erosion.—During the Boundary survey the writer's opportunities for quantitative studies of these vanished glaciers were limited. The studies actually made referred especially to the sheets which, during the maximum of glaciation, occupied Starvation creek and Kintla creek valleys. In each case the usual signs of direct ice-erosion were not found above the 6,100-foot contour along the middle and lower part of the valley. In that part, the Starvation glacier was about 1,000 feet thick, while the Kintla glacier was about 2,000 feet thick. The bottom gradients for each trunk glacier were, respectively, 100 feet and 50 feet to the mile. The surface gradients for the trunks of the glaciers were of the same order but those for the high level branches must have been much steeper, from 200 feet to 1,500 feet or more to the mile. The thrusts exerted by these high-grade affluent streams must have played an important part in developing erosive power in the trunk glaciers.

Yet more important than bottom or surface gradients in causing the prodigious erosion of the mountains, was the bergschrund or master crevasse which, as usual with valley glaciers of all kinds, was kept open between ice and rock. It is generally conceded by glacialists that the conditions for glacial quarrying are most favourable in the depths of the bergschrund. Alternate thawing and freezing in that crevasse loosens the rock which, block after block, is carried away by the ice. Since the bergschrund is developed on the sides

* See similar photographs by W. W. Attwood, published since this paragraph was written. Prof. Paper No. 61. U.S. Geol. Survey, 1909, Plates 2 and 8.

Head-wall of Glacial cirque, summit of Clarke Range. Looking west. View shows contrast of rounded, graded slope formed in pre-Glacial time with very steep, bed-rock slope produced by head-wall recession. Visible part of cliff about five hundred feet high.

as well as the head of a mountain glacier, the valley walls are gradually steepened, giving cross-profiles of the same quality as those in the yet more spectacular amphitheatres up-stream. In other words, trough and fiord erosion as well as cirque development are notably conditioned by the processes operating in the bergschrund.

But it may be quite wrong to attribute the greater part of the erosion in the average trough to plucking. The field studies of Reid, Hess, and others have shown that glacial grinding, with the formation of rock-flour, is competent to deepen a glacier-filled valley with relatively great rapidity. Reid concluded that the average amount of fine sediment contained in the streams draining Muir glacier corresponds to an annual loss of about three-fourths of an inch of rock over the whole bed of that ice-sheet.* Analogous results have been obtained from various studies of the small sheets in the European Alps.† Russell has shown that the coarse morainal deposits formed by the Pleistocene valley glaciers of the Sierra Nevada of California are truly insignificant when compared with the amount of rock which must have been removed to shape the many U-shaped troughs mouthing in Mono valley.‡ He concludes that the share of glaciers in this sculpturing work was small, but indicates the possibility that 'other observers, it is true, might give a much higher estimate for the amount of fine material deposited in distant parts of the lake, and conclude that profound glaciation had occurred.' Such observations as those of Reid and Hess suggest that this second view is the more probable one. The recently published, superb map of the Uinta mountains, together with Attwood's accompanying Glacial monograph, shows the reality of Pleistocene glacial erosion on a great scale in that range.§ The results of bergschrund erosion are there strikingly similar to those observed in the Clarke and Lewis ranges (see especially plates 2, 7, and 8 of the monograph). On the other hand, the moraines at the piedmont slopes of the Uintas are much too small to match the volume of rock which has clearly been removed from their troughs by glacial erosion. The missing material must be sought in the fine silts occurring in broad sheets far outside the range.

In view of these and many other observations made by glacial experts the writer has come to the conclusion that glacial scour or abrasion proper has been largely, if not chiefly, responsible for the demonstrably great glacial erosion in the low-gradient portions of the master Cordilleran valleys.

The conclusion in no wise conflicts with the obvious fact that the great ice-caps such as the Pleistocene Labrador sheet, performed comparatively little erosion of any kind. The controversy as to the efficiency of glacial erosion has been prolonged partly because insufficient emphasis has been placed on one thorough contrast between ice-caps and mountain glaciers. The former has outflow on all or nearly all radii; the latter have outflow in restricted channels. The feeble excavating power of the larger and generally much thicker sheet is

* H. F. Reid, National Geographic Magazine, Vol. 4, 1892, page 51.
† H. Hess, Die Gletscher, 1904, page 179.
‡ I. C. Russell, Eighth Annual Report, U.S. Geol. Survey, pt. I, 1887, p. 349.
§ W. W. Attwood, Prof. Paper No. 61, U.S. Geol. Survey, 1909.

a function of its necessarily low velocity of flow. The spectacular erosional effects of the larger valley glaciers, in the deepening of rock basins, the truncation of spurs, and the development of hanging valleys, are to be directly referred to the necessarily much higher velocities of such local ice-sheets.

An example of this contrast may be taken from the Cordillera itself: The vast central ice-cap of British Columbia, though of great average thickness, had relatively small effect in modifying the pre-Glacial forms of mountain and valley. On the other hand, the Chelan valley glacier of Washington, covering in all about 550 square miles, has shaped one of the grandest mountain-troughs in the world, deepening it and truncating the adjacent mountain spurs so as to give a valley form like that of a Norwegian or Alaskan fiord. In the process the rock-basin of Lake Chelan was sunk at least 300 feet beneath the present level of the sea.* We must believe that the climatic conditions were here very similar to those which bred the British Columbia ice-cap. The different power of erosion is simply a matter of concentration of flow. The channel of outflow at maximum glaciation was only about three miles in width at the Narrows of Lake Chelan. The area of ice drained through this trough was that of a circle about ninety miles in circumference. The width of the effluent Chelan glacier at the Narrows corresponds to only twelve degrees of arc measured on that circumference. The outflow of the British Columbia ice-cap must have been on the average much less than one-tenth as much concentrated. The Labrador ice-cap at maximum glaciation was free to move on nearly all radii, so that, if its climatic conditions were like those of the Chelan field, the concentration of flow was nearly thirty times as great in the Chelan valley as the flow at the average point near the edge of the Labrador ice-cap. Trouton's experiments seem to demonstrate that abrasion or scour on bed-rock is directly proportional to the velocity of the ice. † Hence we may believe that the Chelan glacier on a flat or even a reversed bottom gradient, abraded its floor about thirty times faster than the Labrador ice-cap scoured its larger area. If the Labrador ice-cap lowered its bed on the average fifty feet in solid rock, we can readily agree that the powerful mountain glaciers showing concentration like that at Lake Chelan, could in the same time lower their beds locally for thousands of feet in the living rock.

To the present writer, therefore, it appears that there is no real ground for controversy regarding the efficiency of glacial erosion. The principle of concentration of ice flow in mountainous topography has been stated by several writers who are engaged in the controversy. Perhaps because it is so obvious, however, the principle has remained in the background. The purpose of the foregoing note is to point out that the principle is at the essential core of the problem. The glacial erosion actually proved in New York state or in the Midland counties of England, meagre as that erosion has been, is one of the evidences going to show that solid rock thousands of feet in depth has been excavated from Norwegian, Alaska, and British Columbia valleys during the Glacial period. In each case the work accomplished has been a function of the

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* B. Willis, Prof. Paper No. 19, U.S. Geol. Surv., 1903, p. 58 and plate 8.
† F. T. Trouton, Proc. Roy. Soc., Vol. 59, 1895, p. 25.

Winged-out moraine at mouth of Starvation Creek canyon, in Flathead Valley. Galton Range in distance.

velocity of the local ice. An inspection of Reid's map of Muir glacier shows the exceeding importance of concentration of flow in explaining the wonderful stream of rock-flour always pouring out from that ice-sheet. The lowering of its bed by three-fourths inch per year is progressing at a rate amply sufficient to account for fiord-excavation on the largest scale.

The prodigious erosion of the Front ranges necessarily involved the carriage of hundreds, if not thousands of cubic miles of rock-débris to lower ground. On the east, the drift from the Clarke range was first transferred to the piedmont ice-sheets and was then slowly spread over a wide belt on the Great Plains, seldom attaining phenomenal thickness at any point. The detritus carried down the western valleys entered the relatively restricted Flathead trough where even the great North Flathead glacier was incompetent to handle all of the vast load of rock-matter. In consequence, the eastern side of the Flathead trough is covered with many huge moraines which are winged out from the spurs of the Clarke range. The glaciers which occupied the valleys of Kishenehn, Starvation, and Kintla creeks built such moraines, from three to four miles in length, and from 1,000 to 1,500 feet in height. Others of similar dimensions were formed from the drift of glaciers occupying the valleys of Bowman creek, Quartz creek, and Logging creek, south of the Line. Nearly all of these great drift accumulations are mapped in the Kintla Lakes Quadrangle of the United States Geological Survey atlas.

At first the writer was sceptical as to the simple morainal origin of these ridges, but a long search for bed-rock outcrops, attended with entirely negative results, and the general topographic relations of the ridges left little ground for doubt that practically the whole of each ridge is composed of drift. Most of this drift seems to have been, in each case, derived from the adjacent canyons. Boulders of the Siyeh limestone and of the Purcell Lava formation—two prominent constituents of the Clarke range—are very abundant in the drift.

In their lower parts, Kishenehn, Starvation, and Kintla creeks are flowing through the troughs occupied by the corresponding glaciers in their latest stages. These troughs are in fact, the little altered casts of the glaciers as they debouched from the mountains into the Flathead valley. (Plate 52.) The affluent glaciers with the intervening moraines were deflected down the main valley by the southward-moving North Flathead glacier. The moraines are thus systematically directed in southwest directions from the mountain spurs (see Plates 12 and 52, and the Kintla Lakes Quadrangle sheet).

The North Flathead glacier at its maximum stage was from nine to twelve miles in width, and at the Forty-ninth Parallel from 1,500 to 2,000 feet in greatest depth. The highest point at which exotic boulders were found occurs on the 5,100-foot contour on the west side of the valley. It is probable, however, that the glacier at one time covered the mountain slopes to the 5,500-foot contour and perhaps as high as the 6,000-foot contour. The river is 4,000 feet above sea at the Boundary Line.

On the western side of the valley there are no such systematic moraines as those just described on the eastern side. The main glacier was able to remove most of the débris fed to it by the glaciers affluent from the MacDonald range. Those glaciers were not so long nor so efficient in developing cirques as the glaciers draining the Clarke range. The drift material carried to the North Flathead glacier from the western range was therefore very much less abundant than that issuing from the eastern range. When the main glacier finally wasted away the new relief of the Flathead valley was unsymmetric, so that the constructional path of the river was located, as at present, on the western side of the wide trough.

Galton-MacDonald Mountain Group.

The rugged topography of the Galton and MacDonald ranges has been largely shaped by local cirque-glaciers. There is plenty of evidence, however, that at the time of maximum glaciation these local sheets were confluent. From the western ridge of the MacDonald range the flooded cirque-glaciers formed a mass of ice continuous with that which then covered the Purcell range and the ranges further west. The erosive effects of the ice-cap have been greatly masked by those of the numerous local glaciers which persisted, long after the surface of the general ice-flood had, by wasting, been lowered from its highest levels. Somewhat prolonged search was therefore required before undoubted evidence of the upper limit of the ice-cap could be obtained in these ranges. The search was necessarily confined to the tops of the ridges dividing the cirques.

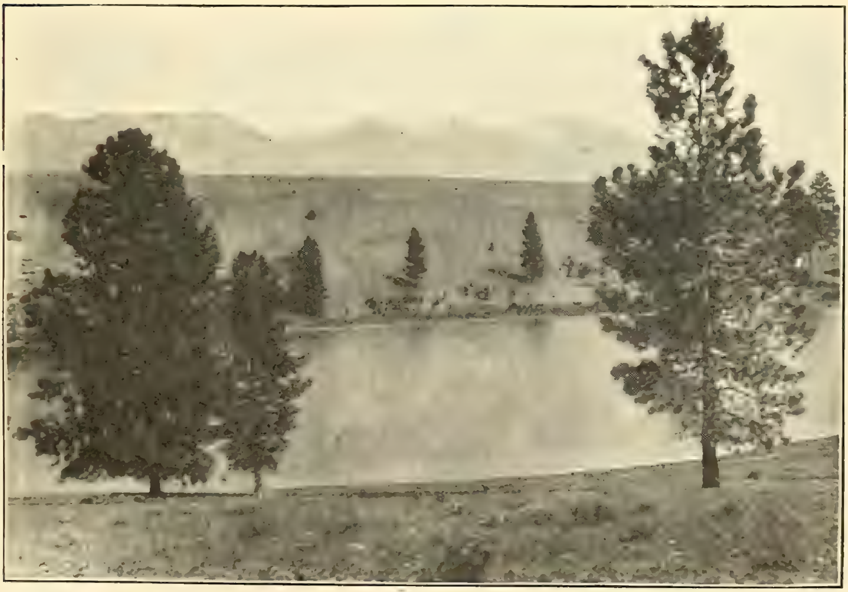
The most favourable locality discovered is that of the long meridional ridge running south from the Boundary slash at 114° 48′ W. Long. On that ridge at the 7,000-foot contour, distinct grooves and striæ were found. These belonged to two different sets, one trending S. 20° E.; the other S. 80° W. In both cases the ice movement was independent of the axes of the flanking cirques. The whole ridge was overrun by ice which, at different times, flowed southward and westward.

A study of the peaks and ridges reaching heights of 7,500 feet or more showed that erratic material was not to be found above the 7,300-foot contour, above which also the other familiar evidences of general glaciation were absent. The writer has concluded that the 7,300-foot contour marks quite closely the average surface-level of the ice-cap in the Galton range and western part of the MacDonald range.

Using the same criteria, it was observed that the ice-cap was limited by the ridge overlooking the Wigwam river on the east. East of that ridge the glaciation seems to have been entirely local, the many cirques draining into the great North Flathead glacier. The latter glacier seems, at its maximum, not to have reached higher than the 6,000-foot contour. Its surface was, therefore, some 1,800 feet lower than that of the ice-cap eight or ten miles distant. Down this steep descent transverse ice streams, flowing out from the ice-cap, helped to feed the North Flathead glacier.

The troughs of the transverse glaciers were later occupied by torrential water derived from the greater ice-masses as these melted. Such an old spill-way is represented in the box-canyon crossing the MacDonald range at the Boundary line. The canyon is now almost dry, but its bed is abundantly supplied with pot-holes and other evidences of heavy scouring by a rapid stream of water.

A. Hanging valley of Phillips creek, cascading into Kootenay river near Gateway. The cascade totals about four hundred feet in height.



B. Drumloidal deposit and water-filled glacial kettle in thick drift of the Rocky Mountain Trench (Tobacco Plains). Looking east, with Galton range in the background.

Within the mountain group the ice of maximum depth—2,800 feet—lay over the Wigwam valley. The average depth of the ice-cap from the eastern divide to Tobacco Plains was about 1,200 feet. The discharge of the ice was in a general southward direction and was largely concentrated in the Wigwam valley and in the Rocky Mountain Trench, though some of the ice flowed eastward into the North Flathead glacier before beginning its southward journey.

In the Galton-MacDonald mountains where crossed by the Boundary belt, only twelve peaks projected, as nunataks, above the surface of the ice-cap and the summit of the highest of these was not more than about 500 feet above the ice. The total area of the nunataks must have been under three or four square miles, or about three to four per cent of the area. In that area about twenty glacial cirques have been mapped, along with a half dozen others mapped in the MacDonald range, east of the Ice Divide.

The western slope of the Galton range and the eastern slope of the McGillivray range delivered many high-level streams of ice to the Rocky Mountain Trench where the ice-cap was of exceptional thickness. Observations in both ranges showing that the continuous cap enveloped all slopes below the present 7,300-foot contour, and the Kootenay river at the Boundary being at approximately the 2,300-foot contour, it follows that, at the time of maximum glaciation, the cap was here about 5,000 feet thick. It is altogether likely that, toward the close of the Pleistocene period, the trench was still occupied by southward-moving ice, a majestic glacier twelve to fifteen miles in width and scores of miles in length.

Distinct lateral moraines formed by the trench glacier were observed east of Tobacco Plains at various elevations from 500 to 2,000 feet or more above the valley floor. When these deposits were made the glacier must have had a width of at least twelve miles. As shown by the deep groovings and by the development of numerous roches moutonnées, the trench was the scene of intense abrasion.

An indication of the notable excavating power of the ice moving down the trench is perhaps given in the fact that the branch valleys in some cases are hanging hundreds of feet above the floor of the trench. As in the case of Cameron Falls at Waterton lake, the probabilities are in favour of the view that these discontinuities of stream gradient are due to more rapid excavation by trunk glaciers as compared with branch glaciers. Such may be the origin of the 500-foot cascade on Phillips creek where it tumbles into the trench. It should, on the other hand, be noted that this cliff may possibly be structurally determined by the retreat of the underlying limestone eastward, down the dip of the beds. (Plate 53, Fig. A.) Since the second explanation cannot be entirely excluded, Phillips creek is not to be surely placed in the class of valleys which 'hang' because of differential glacial erosion.

All of the striæ observed on the floor and side slopes of the trench are directed southward and faithfully parallel to the axis of the valley. The trench glacier completed the work begun during the existence of the ice-cap. The geological work of the cap and that of the trench glacier conspired to produce much of the existing relief of the valley floor at Tobacco Plains. This relief is practically unique in the whole Boundary section, recalling a type of morainal landscape richly illustrated in Wisconsin, New York, Massachusetts, and elsewhere. The glacial deposits flooring the trench are chiefly sandy till often veneered with washed gravels and sands. The till has been subglacially moulded into hills of drumloidal form, some of which have the characteristic, smooth profiles of typical drumlins. (Plate 53, Fig. B.) A score of such lenticular hills are mapped within the five-mile belt. Their longer axes are regularly directed down the trench, a little east of south. The thickness of the drift could not be determined, but it must in places amount to several hundred feet and may average 200 feet or more.

Between the drumloidal hills are numerous pits or kettle-holes, some of which are well over 100 feet in depth; a few hold small lakes. These depressions seem to be of origin quite similar to those occurring in the drumlin areas of the eastern United States and of Europe. Some appear to represent the hollows once occupied by blocks of stagnant ice (true kettles). Others were due to the inevitable inequalities of the subglacial deposition of drift.

Besides the till deposits, veneering kames and sandy plains of plainly water-laid material were observed. Like the drumlins their surfaces have been very little affected by post-Glacial erosion. Occasionally Glacial stream-channels are incised in the drift. In one case the channel ends suddenly in a large kettle-hole, the floor of which lies thirty feet below the bottom level of the channel.

At the eastern edge of Tobacco Plains the drift deposits have been eroded to a depth of from 200 to 300 feet, to form a flat-floored channel about 800 yards in width. This channel is said by the settlers to extend as far north as the Elk river and, according to them, represents a former bed of that stream. The channel fades out on the lower ground a few miles south of the Boundary Line. Its origin was not finally worked out. Fairly large alluvial fans have been built out on the floor of the channel, showing considerable antiquity; it may have been excavated in late Glacial times.

Purcell Mountain System.

For the Purcell system the upper limit of the ice was rather definitely fixed on the high ridge running south from the Boundary Line just east of the 118th meridian. As in the Galton range the limit is practically at the 7,300-foot contour. The highest summit bearing actually observed striæ is 7,100 feet in elevation. The direction of average movement across the ridge-tops was S.S.W. Strong deflections were, however, observed at many elevated points where local topography controlled the directions of the ice-currents. In the lower levels the ice was similarly controlled by bed-rock relief. At all times the flow was southward along the depressions for the ice which filled the Rocky Mountain Trench, the Yahk river valley, the Moyie river valley, and the Purcell Trench. These great troughs naturally controlled the drainage of the ice flood.

The depth of the ice over the Yahk river valley must have been about 4,000 feet; over the Moyie, 4,500 to 4,600 feet; over the Purcell Trench, about

5,500 feet. The average depth for the whole Purcell system at the Forty-ninth Parallel was about 2,500 feet. At the summits of the Yahk and McGillivray ranges, a few small nunataks projected a few hundred feet. Elsewhere the whole mountain system, including ninety-nine per cent of the Boundary belt, was completely smothered under the ice. This fact doubtless partly explains the relative rarity of cirques in these mountains (about a dozen in the Boundary belt). The relief was not sufficient to generate valley ice-sheets which could endure long enough for the quarrying out of many amphitheatres. The glacial erosion of the Purcells was thus chiefly accomplished under the all-mantling ice-cap and not at the head-walls of local glaciers.

Five or six of the cirques observed in the Boundary belt have been opened on the basset edges (those facing the direction of dip) of the strata. The head-wall of each cirque has been driven into the mountain against those edges. The relation shows vividly the contrast in the essential processes of normal subaërial erosion when compared with the process of cirque development.

Throughout the Boundary belt drift deposits may at intervals be found in the Purcells, but they are not so heavy as in the more westerly ranges. The deposits are naturally irregular and do not declare themselves readily as belonging to definite or recognized types. It was noted that the slopes on each side of the Yahk river, up to a level about 200 feet above it, have been washed very clean of gravels and other drift material. The explanation is sought in the hypothesis that toward the close of the Glacial period, this valley was occupied by a very large and powerful river which was fed by the rush of waters from the melting ice-cap farther north. This temporary river must have been over a mile wide and at least 200 feet deep in the middle part. Its point or points of origin and its course outside the Boundary belt were not determined. We have here a type of many such problems in the nature and effects of late-Glacial drainage of the Cordillera. Many seasons of special field work aided by extensive, accurate mapping, will be necessary before this chapter in geological history can be written.

Between Porthill and McKim Cliff, a distance of four miles, the Purcell Trench is floored with a thick mass of obscurely stratified clay, which contains a few scattered drift boulders. The clay is of varying thickness and fills depressions in the rock bench which outcrops at intervals through the same width of the trench. Some patches of true boulder-clay and of washed gravels intervene between the stratified clay and bed-rock. The gravels and boulder-clay have the properties of the usual Glacial deposits. The massive stratified clay is fine-textured and very homogeneous. It extends from Goat river six miles north of the Boundary to some undetermined point south of Copeland, Idaho. As shown on the map, the surface of the bench is not flat but varies from 2,000 feet or less to 2,300 feet in elevation.

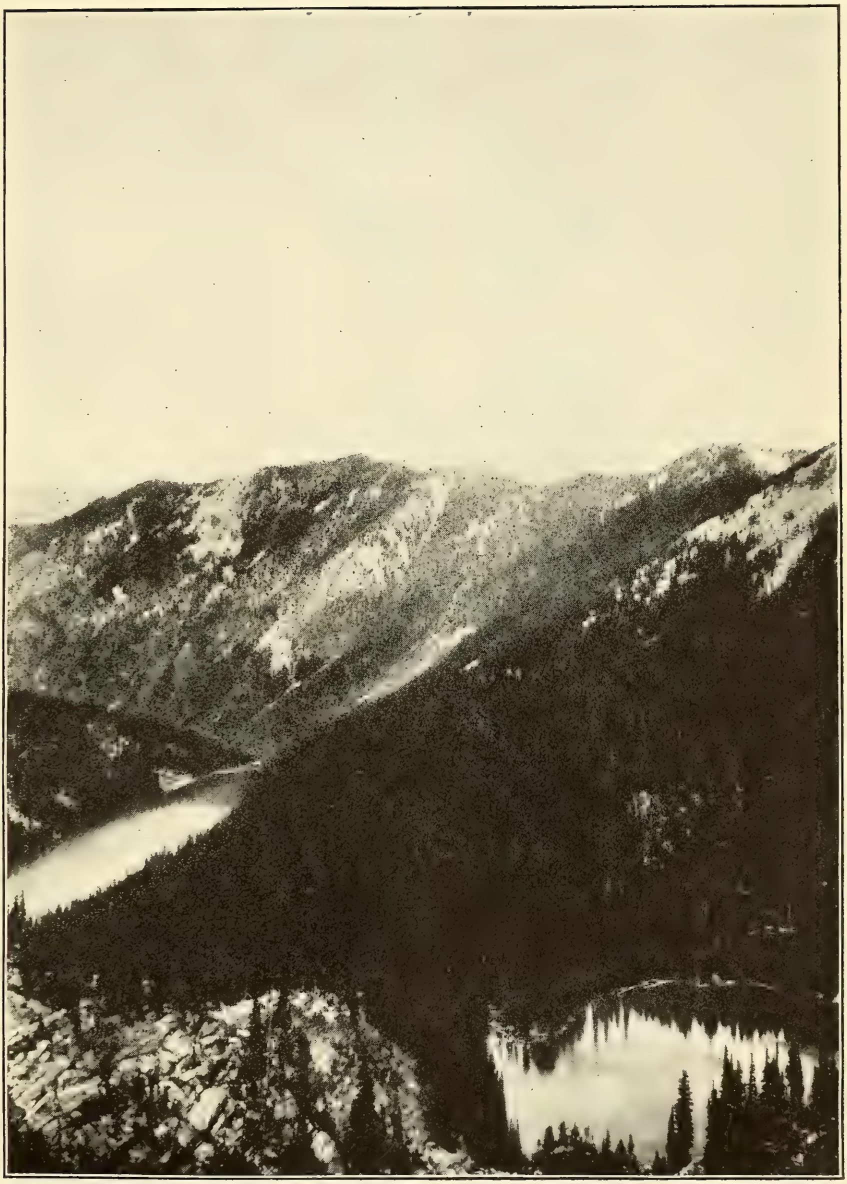
From the fact that the properties of the clay are sensibly like those of the Kootenay river delta which is to-day growing out into the lake below Creston, the writer is inclined to the view that the stratified clay of the Porthill bench was laid down in a temporary lake. If this be true the western half of the trench between Creston, Porthill, and points farther south, must have been ice-filled. The main Purcell Trench glacier then occupied the site of the present delta of the Kootenay and furnished the western shore of the postulated temporary lake. The lacustrine clay now exposed in the Porthill bench may in part have been derived from the débris washed out of the trench glacier, but the topographic relations suggest that the late-Glacial Goat river delivered most of the clay to the temporary lake. East of Copeland the clay bench is bounded on the east by a strong moraine which extends southward from the mountain-spur separating the Moyie river valley from the Purcell Trench. This moraine is homologous to those winged-out from the Clarke range into the Flathead valley and shows the place of meeting between the Purcell Trench glacier and the Moyie glacier. The Porthill clay is a later deposit formed after a pronounced shrinkage of the trench glacier, which had then retreated to the western half of the trench. The bed of that diminished ice-sheet was, on the final disappearance of the ice, filled with the waters of Kootenay lake. The building of the Kootenay river delta from Porthill to Kootenay Landing, a distance of twenty miles, is the work of post-Glacial time.

Selkirk Mountain System.

The summit ridge of the Nelson range located a notable and abrupt change in level of the ice-cap at its maximum strength. From Mt. Ripple eastward this upper limit occurred near the present 7,300-foot contour. On the western side of the divide the surface of the cap declined rapidly so as to reach little, if any, higher than the 6,800-foot contour. At the Columbia it appears to have been as low as the 6,500-foot contour. Since the mountains west of the high ridge of the Nelson range were completely buried by the ice-cap, the latter figures have not been based on direct observations. The values have been obtained by interpolating on the flat curve joining observed points in the Nelson range and in the Rossland mountains. Notwithstanding this sharp change of level for the ice-surface, it seems best to regard the ice-sheets on each slope of the Nelson range as part of the one ice-cap. The summit ridge was simply a long nunatak within the great sheet.

The observations on the striæ occurring on the ridges and peaks showed that the general movement of the ice on the eastern slope of the Nelson range was in the direction S. 30° E. On the western slope, as over the Bonnington range, the ice moved, on the average, about S. 10° E.

Cirques are common along the belt of the Nelson range nunatak, but are rare to the westward, where for a distance of forty miles all the peaks of the ten-mile belt were covered by the ice. (Plate 54.) The generation of the cirques has here, as usual in the Cordillera, caused the residual peaks and ridges to show systematic slopes. The slopes facing southwest, south, and southeast are, as a rule, much less steep than those facing northeast, north, and northwest. The reason is obviously due to the varying strength of the glaciers as they and their respective snow-fields thickened in the shadows of the northerly slopes or thinned under the direct solar rays beating on more southerly slopes. An illustration of the resulting asymmetry of the peaks is given in Plate 19.



Tandem cirque-lakes near summit of Nelson Range, seven miles north of Boundary line; looking northwest.

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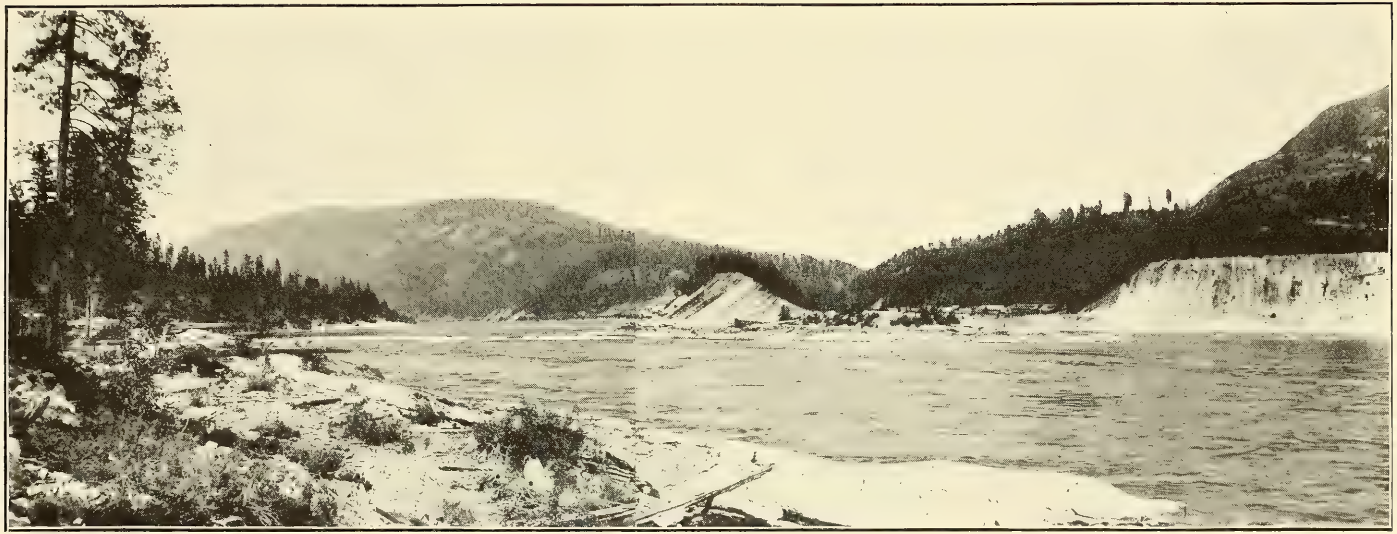

Looking east across the Columbia river to Boundary Town, lying in the old gravel-floored bed of the Pend D'Oreille river. The Pend D'Oreille now enters the Columbia at a point behind the steep gravel scarp in the middle of the view.

Abandoned channel of the Pend D'Oreille river at Boundary Town. Much alluvial gold has been taken from the channel gravels. The confluence of the Pend D'Oreille and Columbia rivers on the right. The ridge in the center is composed of terrace sands and gravels.

25a—vol. iii—p. 588.

The cap was 4,000 feet deep over the Salmon river, and at least 5,200 feet deep over the Columbia river.

The evidences of greatly increasing abrasion and plucking power as the depth of ice increased are very striking as one descends from the heights to east or west of the Columbia river, down to the floor of the valley. Yet, volume for volume, even this thick part of the ice-cap was vastly inferior in quarrying efficiency to the relatively insignificant cirque-glaciers at the summits. The average depth for the whole Selkirk system in the ten-mile belt was about 2,500 feet.

Drift deposits are not abundant on the eastern slope of the range. They become thicker and more important as the Columbia river is approached. The grinding up of the auriferous rock along the Pend D'Oreille, followed by the washing of large quantities of the rock-flour and sand into and along that valley, has led to the local concentration of gold-bearing gravels. (Plates 55 and 56.)

The well-known terrace sands and gravels of the Columbia valley were accumulated during the slow retreat of the ice-cap and local glaciers. At the Forty-ninth Parallel the surface of the main terrace is about 80 feet above the river. (Plate 73, Fig. A.) Four other terraces occurring on the valley slopes about five miles southwest of Waneta, were barometrically determined to be 350, 400, 525, and 725 feet higher, but these are probably of quite local origin and do not represent a corresponding amount of excavation by the Columbia in the gravel-filling of its own valley.

Columbia Mountain System and the Interior Plateaus.

From the Columbia river to the Similkameen river, a distance of 100 miles, the mountains crossed by the Boundary are at only two places high enough to show the maximum height of the ice-cap. The one locality is Record mountain ridge and its northern continuation toward Old Glory mountain. The other favourable locality is at Mt. St. Thomas and the ridge running southward from it. The usual criteria for both ridges showed that the general cap did not submerge any slopes higher than the present 6,600-foot contour. Observations made on Mt. Chopaka just west of the Similkameen river, showed that the upper limit of the ice was there at about the 7,200-foot contour. The surface of the cap thus slowly declined from the Okanagan range to the Columbia river at an average rate of six feet to the mile.

The ice-cap was about 4,500 feet deep over Sheep creek valley, Christina lake, and the Kettle river valley. The maximum thicknesses in the Boundary belt, about 6,300 feet, were to be found over the Osoyoos lake and Similkameen river valleys. The average thickness throughout the hundred miles was about 3,000 feet.

The average directions of ice-movement across summits were, for the Rossland, Christina, and Midway mountains, about S. 20° E. At several elevated points in the plateau-like Anarchist and Kruger mountains, well-marked striæ and grooves showed that the ice moved nearly due east, evidently flowing from the high Okanagan range toward the lower ground of the Interior Plateaus.

In the middle of the 100-mile section R. W. Brock has made a study of the glacial phenomena in the area of about 220 square miles included in the Boundary Creek district. A brief statement of his results regarding the direction of ice flow may be quoted; it corroborates the present writer's conclusions regarding this area.

> 'The direction of the movement as shown by the striation on the polished surfaces of the rocks, is influenced by the local topography, the ice having a tendency to move in the direction of the principal valleys. On the summits of ridges and mountains, it shows greater independence. It varies from S. 15° W. to S. 41° E. An average of a great number of readings gives S. 18° E. as the general direction of flowage.'*

The drift mantle in the Midway mountains and Belt of Interior Plateaus is thicker and more continuous than in any other part of the whole transmontane section. The erosion of the bed-rock is much less conspicuous than in the ranges farther east or in the Cascade ranges. Well characterized roches moutonnées are not common. The bed-rock is often weathered more deeply than is the rule in other parts of the bed of the ice-cap. The facts show that in this part of the Cordillera, the ice-cap, thick as it was, performed relatively little erosion. Its activities were largely spent in transporting and depositing the abundant drift material won from the Interior Plateaus and that brought to the ice-cap by the feeding glaciers which drained the névé of the Cascade range. The explanation of the feeble erosive power is to be found partly in the fact that the front of the ice-cap during its maximum extension lay not far south of the Forty-ninth Parallel; yet still more clearly in the fact that the average speed of ice-movement must have been low in the whole ice-cap area. The character of the drift is highly variable; it includes much boulder-clay, as well as washed drift.

As the general ice-cap wasted away, the uplands were uncovered and, during a considerable time, the Okanagan, Similkameen, and probably other valleys were occupied by local glaciers of great size. These were responsible for the intense erosion of the valley bottoms and sides, which are therefore characterized by abundant polished and grooved ledges of fresh rock. The increase in the erosive effects is very noticeable as one descends the 4,000 feet into the Osoyoos lake trough.

The bed-rock sides of the trough are at many points covered with local and discontinuous terraces composed of sand or of roughly stratified gravel. The highest observed deposit of the kind was found at the 3,700-foot contour on the east side of Osoyoos lake. Others at a dozen or more different levels occur on both slopes. (For locality see Plate 63). These are almost without question deposits of rock-débris which were washed into the valley and lodged between the valley wall and the Okanagan glacier. As the ice-sheet diminished these lateral terraces were formed at lower and lower levels. The resulting step-like forms are not, therefore, stream-cut terraces but are little-altered constructional

* R. W. Brock, Ann. Rep., Canadian Geol. Survey, Vol. 15, 1902, pp. 94 and 96.

reliefs formed in late Glacial time. Closely allied to these linear terracelets are truncated fans which at various levels were washed from the principal branch valleys into the trough and against the ice, the gravel-sand deposit in each case backing up into the branch valley. A deltoid form was thus produced, with the base of the delta marking the ice-wall which retained the detritus on the side of the main valley. These high-level fans are themselves sometimes terraced as if the ice-wall had lowered by successive stages.

The wide benches slowly rising from Osoyoos lake to the mountains on either side where their surfaces are about 200 feet above the lake level, are composed of sandy gravel. This forms a thick, late-Glacial deposit. It has been washed by slowly moving water, which has often 'leached' out the finer débris and left a thin cover of gravel over a great part of each bench. The details of form suggest that the washing was performed by the waves and currents of the lake during its expansion across the whole valley and during the slow sinking of its level. Both climatic change and the down-cutting of the outlet are responsible for the fall of the water. The maximum depth of the lake was doubtless contemporaneous with the close of the Pleistocene period. Since then the roughly graded valley-floor has been gullied by the small streams entering the lake from east and west. Other channel-like depressions parallel to the valley axis may represent the spill-ways of the waters derived from ice which, in late Pleistocene time, was melting farther up the Okanagan valley.

An interesting effect of glaciation is to be found in the peculiar drainage re-arrangements in the lower part of the Similkameen river. The river passes the Boundary at Mt. Chopaka ridge, following a broad U-shaped trough which continues southwardly to and beyond Loomis, Wash. Two miles north of Palmer lake (see Chopaka Quadrangle of the United States Geological Survey Atlas), the river abruptly leaves the trough and crosses Kruger Mountain plateau in a deep canyon which also carries the branch of the Great Northern railway on its low grade up the river. The forms of the valleys and the course of the river have been affected by the activities of the late Pleistocene local glaciers. An account of this and other important diversions of principal Cordilleran rivers by Glacial activities is given in a remarkably suggestive, all too brief, paper by Willis.*

Throughout the whole hundred-mile section, well-developed glacial cirques are entirely wanting. The field evidence is clear that apart from the few large valley glaciers already noted, there were very few local sheets to survive the ice-cap as it finally disappeared from the mountains.

Okanagan Range.

The western edge of the ice-cap at the Forty-ninth Parallel was situated in the Okanagan range, from twenty-five to thirty-five miles west of the Similkameen river. Many accordant observations showed that on the slopes of the ridge bearing Cathedral Peak and Park mountain, the upper limit of the ice

* B. Willis, Bulletin 40, U.S. Geol. Survey, 1887. Cf. W. L. Dawson on 'Glacial Phenomena in Okanagan County, Washington,' American Geologist, Vol. 22, 1898, p. 203.

followed in general the 7,800-foot contour, though, of course, the surface rose and fell with the varying conditions of topography and exposure of the névé. The ten-mile strip of country between these mountains seems to have borne a massive, continuous snowfield which shed ice to the westward as well as to the eastward. Between the two mountains, the Ashnola valley at the Forty-ninth Parallel carried a load of about 3,000 feet of ice. Below the 7,800-foot contour the peaks and ridges to the east of Cathedral Peak were covered by the ice. The cap was in part supplied by cirque glaciers which headed among the summit ridges. At Mt. Chopaka, twenty miles to the eastward, the surface of the ice-cap followed the 7,200-foot contour. From that mountain to Cathedral Peak the surface of the ice rose, on the average, some thirty feet to the mile.

Above the upper limit of the ice the peaks are greatly disintegrated and wide-spread felsenmeers are usually present. At those levels the granites were sometimes seen to be deeply weathered, with the generation of many boulders of secular decay. Below the ice-limit, the erosive effects of the ice-cap are very striking, often rivalling in intensity those observed on the bed of the Labrador ice-sheet. The efficiency of the ice-cap as an erosive agent in this range is remarkable in view of the fact that the average depth of the ice was little more than 1,000 feet, while we have seen that ice three times as thick was incapable of performing much erosion on the lower mountains across the Similkameen. The difference in erosive power is doubtless to be explained by the steeper surface, bottom gradients, and frequent local concentration in flow of the ice mantling the Okanagan range.

The strong topography naturally influenced local ice-currents in high degree. It is highly probable that the ice-cap was succeeded by many cirque glaciers, the erosive effects of which are superimposed on those of the older ice-cap. Care was therefore taken to note the striations and furrowings engraved on the higher divides where cirque glaciers could not have flowed. Such readings were not numerous but they showed that the average direction of movement for the ice-cap was about S. 30° E.

About twenty-five cirques or cirque-like gulches occur in the range where crossed by the Boundary belt. These have been sunk in granitic rocks in which the natural joint planes render glacial plucking specially easy. As usual the attack of the cirque glaciers has often left the ridges asymmetric, with the steeper slopes on the east, northeast and north.

West of Park mountain and Peeve Pass the great snowfield shed local, often confluent, glaciers southwestward toward the Pasayten valley. Definite proof that the direction of movement was thus different from that on the eastern slope of the Okanagan range, was furnished at several points. One of the most conclusive evidences was found in the fact that the 6,800-foot ridge southwest of the 'Basic Complex' on the Park mountain divide, is abundantly sprinkled with boulders of the rocks peculiar to the complex. These basic boulders were immediately seen to be erratic as they lay on the gray ledges of the Remmel granite. From this ice divide westward the glaciation was not general; each mountain-block was a local center of accumulation from which great valley

Winter-talus ridge on southern wall of glacial cirque, Okanagan Range.

glaciers streamed away to merge with the still heavier trunk glaciers moving along the Pasayten, Skagit, and other master valleys.

In some of the cirques of the range there occur ridges of coarse rock-débris such as that illustrated in Plate 57. These ridges are from one to three hundred yards or more in length and are best developed along the southwest and south walls of northerly facing cirques. The axis of each ridge is generally somewhat curved in ground-plan, with the concavity facing the concavity of the cirque-wall. The height of the wall of angular rock fragments varies from five feet or less to thirty feet or more. In each case most of the accumulation of débris evidently took place at such times as the cirque was occupied by a heavy bank of snow. This was drifted to specially great depths (fifty feet or more) against the relatively shaded sides of the cirque. From the cliffs above

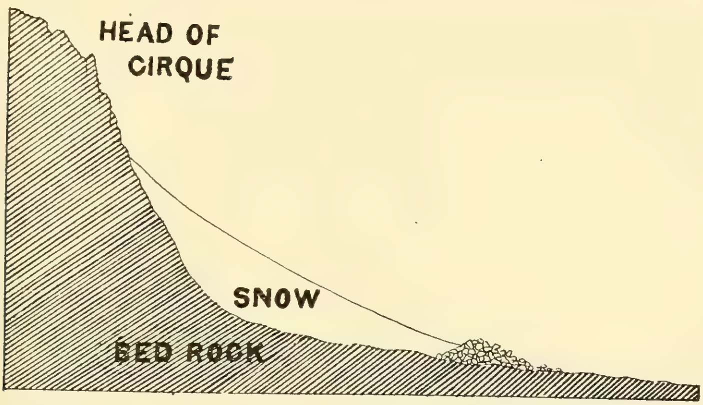

FIGURE 41.—Diagrammatic section showing origin of a "winter-talus ridge".

the snow-bank, frost rifted away masses of rock which fell upon the snowdrift, to roll down its steep surface and lodge at its foot, and thus clear of the cirque wall. This action has, in places, been continued long enough to form long and quite remarkable piles of rock-fragments on the floors of the cirques. Since these special accumulations of débris are dependent on the formation of heavy snow-banks and on specially rapid frost-action before the summer heat has melted the snow in large measure, the wall-like piles may be called 'winter-talus ridges' (Fig. 41). Other fine examples were observed in the glacial amphitheatres of the Rocky Mountain ranges.

HOZOMEEN RANGE.

The extensive massif culminating in Castle Peak was one of the centres of ice-dispersal during the heavy glaciation of the Hozomeen range. Valley glaciers from 1,000 to 2,500 feet deep moved out from the central snowfield toward all four quarters of the compass. When the sheets were at their maximum thickness many of the high spurs were submerged. Many erratics from the Castle Peak granite stock were observed at the 6,850-foot contour on the ridges of the north, indicating a local streaming of the ice toward the Belt of Interior Plateaus in British Columbia. Other erratics from the same source are sprinkled over the Hozomeen ridge to at least the 6,200-foot contour, showing again clearly that a heavy, broad stream of ice from Castle Peak moved across the deep canyon of Lightning creek and became confluent with the main glacier flowing down the Skagit valley. As the climatic conditions changed, the ice-currents became more localized in the valleys, but the erosive work, including the formation of cirques and the sharpening of the ridges by head-wall recession, continued long after the maximum glaciation was passed. As a result the Hozomeen range is one of the most rugged of those crossed by the Forty-ninth Parallel.

We have seen that the upper Glacial limit of the ice-cap on the west side of the Okanagan range was 500 or 600 feet lower than the upper limit in the eastern half of that range. It is also quite clear in the field that the Hozomeen, as well as the Skagit ranges were not covered by such continuous ice-caps as were the ranges farther east. Yet we must not conclude that the precipitation of snow was any less in the former ranges. The probabilities are rather in favour of the view that the Hozomeen and Skagit ranges received a somewhat higher annual proportion of snow than the Interior Plateaus, the Columbia mountain system, or the Selkirk mountain system. The local character of the glaciation in the Hozomeen range, as in the Skagit range, was rather due to the fact that the pre-Glacial canyons were there deeper than those of the eastern ranges, and the valley gradients were steeper. From the opening of the Glacial period the outflow of ice toward the sea or toward the unglaciated tracts must have been much faster in the western ranges. Their local glaciers, by rapidly deepening the canyon, must have attained still greater ability to drain the snow-fields and so lower the average level of the ice. East of the Okanagan range, for 300 miles, the Cordillera was flooded in ice, the fairly even surface of which was broken by a few nunataks, like islands in a vast lake. West of that range a general flood was impossible, since the pre-Glacial topography offered many deep channels along which the ice was, with relatively high speed, drained away.

Of these effluent channels the Skagit valley was the master for the Hozomeen range and for the eastern slope of the Skagit range. Through that wide and deep trough an enormous stream of ice moved down, to swell the piedmont sheet in Admiralty Inlet.

Skagit Range.

Though the Skagit range did not bear a continuous ice-cap in the Pleistocene period the effects of powerful glaciation are manifest wherever the range has been explored. With the possible exception of the Clarke range, no other part of the Cordillera on the Forty-ninth Parallel can

Wooded boulder-moraine forming dam at lower end of Chilliwack Lake.

Looking up Chilliwack Lake from point near its outlet.

rival the Skagit range for ruggedness. This property, especially as relates to the steepness of slopes, the prevalence of knife-edges, ridges, and sharp horns, is in part the result of prolonged erosion by Pleistocene local glaciers. The descendants of those glaciers are represented by numerous small sheets occupying the northerly slopes of the higher massifs from Glacier Peak to Tamihy mountain. In Glacial times the incomparably vaster rivers of ice must have headed at about the same levels as the existing glacierlets, that is above the 7,000-foot contour. From those heads to the sealevel the average descent on the west slope was from 200 to 400 feet to the mile. At the maximum glaciation the master glaciers of that slope had depths from 4,000 to 5,000 feet. These colossal bodies moving on gradients of over 100 feet to the mile were plainly competent to perform rapid geological work. There is little wonder that the longest of the sheets occurring in the Boundary belt—the Chilliwack glacier—has produced a long, continuous U-shaped trough, fiord-like in its cross-section. Such is the character of the Chilliwack valley from the head of the lake to the debouchure thirty miles below. The intensity of the Glacial erosion is shown by the fact that the mountain spurs which in rhythmical alternation overlooked the pre-Glacial valley to right and left, have been truncated on a large scale (Plate 59). In evident fashion, though in less degree, the effluent glaciers occupying the valleys of Depot, Silver, Middle, Slesse, and Tamihy creeks, have similarly driven back the lateral spurs, greatly steepened the valley walls, and reduced intervening ridges to razor-back profiles for miles together. Above the ridges tower the pinnacles like Sleese mountain, Tamihy mountain, Glacier Peak, and many others which lend their grandeur to the panoramas visible from elevated stations. Just below the summits glacial amphitheatres lend not inferior variety of relief to the rugged range. Tandem cirques, sometimes holding picturesque lakelets in each, are here, as in the Selkirk and Clarke ranges, not uncommon.

Chilliwack lake, one of the most beautiful in the Cordillera, is held at its level of about 2,000 feet above sea by a strong boulder moraine, which in a smooth, graceful curve of 2,000 yards loops across the valley bottom. (Plates 58 and 60). As shown by soundings in the lake (265 feet deep, 300 yards off shore from the middle of the moraine), the moraine seems to be at least 350 feet high. Owing to lack of sounding-line the maximum depth of the lake was not determined. Two thousand yards below the delta at the upper end of the lake, the depth in the middle was measured at 198 feet. The boulder deposit is continuous for more than a mile down the valley, descending by two remarkably regular steps about 150 feet in that distance. The boulders are of all sizes up to those thirty feet long and fifteen feet thick, growing generally smaller down the valley. Almost all of them are composed of the same granite which surrounds and underlies the lake. The moraine was evidently formed during a long halt in the recession of the Chilliwack glacier. At the outlet a 75-foot notch has been cut through the moraine. Thence the Chilliwack river, on a gradient of nearly 100 feet to the mile, rushes on its torrential way to the Fraser flats.

In the lower part of the Chilliwack river valley, from the confluence of Slesse creek to the head of the rocky defile where the river emerges from the mountains, a thick deposit of Glacial clay forms a high bench on the north side of the valley. The cliffed front of the bench opposite Tamihy creek is some 300 feet above the river. The surface of the bench rises gradually northward another 350 feet to the rocky slopes of the mountain from 1·5 to 2 miles from the river.

The clay is generally massive and without evident stratification. Striated boulders of many different rock-species are fairly common in the mass. The writer has concluded that some of the deposit is true boulder-clay. Most of the material probably came down the Chilliwack valley, but some of it may have been carried over the ridge to the north by the huge glacier which moved southwestwardly down the Fraser trough. Some of the more homogeneous clay may have been laid down during a temporary Glacial damming of the lower Chilliwack valley.

In post-Glacial time the river has cut its gorge through the clay and the débris has gone to form a part of the low grade alluvial fan spread out over the Fraser flat from Sumas lake to Chilliwack village. The radius of this fan averages some seven miles, the apex being about seventy-five feet above the Fraser at average flood-level.

During the maximum glaciation the Chilliwack and Fraser ice-sheets were confluent at such elevations that they may be regarded as forming part of the Pacific piedmont glacier. On the tops of the ridges south of Cultus lake, erratic boulders of what appeared to be Chilliwack lake granodiorite were found at elevations up to 4,700 feet. The long ridge between Cultus and Sumas lakes (3,000 feet high), and also Sumas mountain were completely submerged by the Piedmont sheet. Over the Fraser flats the latter must have been at least 3,000 feet thick and it may have been, at one time, over 4,000 feet thick. The thickness doubtless decreased considerably toward the sea where the main piedmont sheet was moving southward down the Gulf of Georgia, to join the Puget Sound piedmont at the Strait of Juan de Fuca. The Puget Sound sheet, according to Willis, had a maximum general thickness of about 2,500 feet.*

There remains to be noted a late-Glacial deposit of large size which is now to be seen, in plateau-remnants, between Westminster and Point Roberts. It consists of a great sheet of gravels and sand which, apparently, was washed out from the Fraser valley and distributed over the floor of the Gulf of Georgia. The general coarseness of the material betokens torrential currents, suggesting that the streams issued from the Fraser glacier as its front long stood near the present head of the river delta. The occurrence of steeply dipping, typical beach-gravels within the mass now exposed well above sea-level, shows that the land then stood lower than now (Plate 61, Fig. B). The deposit seems, thus, to be a coarse-grained delta, built during later Pleistocene time by the waters rushing out of the master ice-sheet which occu-

* B Willis, Tacoma Folio, U.S. Geol. Survey, 1899.

Looking up Chilliwack Lake over forested morainal dam of the lake; from a point north of the Chilliwack River and twenty-five hundred feet above the lake.

pied the Fraser trough. On the disappearance of the ice the river has cut away large tracts of the old delta, has built a clayey flood-plain over the erosion surface, and is to-day pushing a new silty delta into the gulf. The old delta is now represented by flat-topped remnants rising 200 feet or more above sea. These extensive plateaus are bounded by sea-cliffs, and by the steep scarps cut by the Fraser as its channels swing powerfully across its present flood-plain. (Plate 61).

Such are the conclusions to which the writer has come as a result of short study of the gravel plateaus in 1901. Further field-work may, however, show that their history has been, in some respects different; the problem is worthy of special, more prolonged study.

Summary.

So far as they go, the observations made during the six seasons of field work do not imply more than one period of glaciation. It does not follow, of course, that there were not two or more distinct glaciations of the boundary belt in Pleistocene time; the evidence on this point is as yet negative. In a region of such strong topography we should hardly expect the deposits of an earlier epoch to have been preserved if a later epoch of general glaciation had intervened. The fresh condition of both rock ledges and drift deposits is so similar to that observed in the eastern region of Wisconsin glaciation that one is forced to the belief that the Cordillera was ice-capped in that latest phase of the Pleistocene.

The Forty-ninth Parallel section is specially instructive as showing the enormously greater erosive efficiency of local valley glaciers as compared with the efficiency of a regional ice-cap. The ice-tongues of the Rocky Mountains and of the Cascades have effected great changes in the forms of the mountains, while much of the Cordilleran interior, though simultaneously covered by ice of greater thickness, has suffered relatively little change in the pre-Glacial topography. The difference of result is explained partly by the much greater prevalence of bergschrund in the ranges affected by local glaciation; and partly by the higher average velocity of the master local glaciers as compared with that of the ice-cap. The comparison is specially illuminating since both ice-cap area and local glacier areas were characterized by essentially similar climatic conditions. In both cases snow-fall and rate of ablation were much the same in these different mountain belts. The relative feebleness of the Cordilleran ice-cap in erosive effect is fairly matched by the relative feebleness of the Labrador ice-cap on the plateau-like surface of eastern North America. In contrast to both stand the Pleistocene glaciers which lay in the Chilliwack and Chelan valleys, or those which occupied the Rocky Mountain and Purcell trenches in late-Glacial time. All of these trough glaciers eroded the living rock on a spectacular scale.

The details given regarding the thickness of glaciers, direction of flow, character of drift deposits, etc., are substantially similar in quality to those on which Dawson based his generalization regarding the Pleistocene glaciation of British Columbia and Alberta. The more important new facts are summarized in the diagrammatic section of Plate 49. Because of the limited area covered by the Boundary survey almost no pertinent facts have been added to the important theory of drainage modification in the Cordillera through glaciation. Willis's acute discussion of this topic, though it covers only a relatively small part of the glaciated tract, is still the most important contribution to this subject. A further study on the same line is only one of the many repaying subjects for investigation by glacial experts in the Cordillera.

View of the gravel plateau representing the late Pleistocene delta of the Fraser river; two miles east of Ladner's Landing, Fraser river. The top of the plateau is over three hundred feet above the level of the river.

Detailed section in the sands and gravels of the Pleistocene deposit represented above. Sea-cliff at Point Roberts. The highly inclined gravel beds may represent a beach or spit deposit.

Photograph showing relatively rapid erosive effects of glacierlets with very small accumulators (snowfields). Summit of ridge between Middle and Slesse creeks, Skagit Range; looking south.

Small glacier deepening cirque, about seven thousand feet above sea. On Boundary line, north of Glacier Peak, Skagit Range.

CHAPTER XXII.

PHYSIOGRAPHIC NOTES ON THE FORTY-NINTH PARALLEL SECTION.

A general account of the physiography of the Cordillera in the vicinity of the International Boundary, even if it embraced merely the facts now in hand, would alone occupy a stout volume. The present report would grow out of its intended proportion if such additional matter should enter it. In the present chapter it has seemed better to restrict the physiographic treatment of the region to a brief discussion of some of the observations made in the field, together with an equally brief note on the general theory of the topographic development in the Cordillera. Restricted in scope as this chapter is intended to be, it does not cover, except in the most incidental way, the climatological side of the physiography. The following notes relate essentially to the geomorphology, that is, to the genetic discussion of the land-forms encountered in the traverse across the mountain chain.

Origin of the Master Valleys.

In the chapters dealing with the bed-rock geology we have seen that the subdivision of the Cordillera on a purely topographic basis is to some extent supported by the structural geology determined along the Forty-ninth Parallel. This support consists in the fact that the topographic subdivision is partly a genetic subdivision and perhaps so far a final one.

West of the eastern faces of the Clarke and Lewis ranges, where the ragged escarpments on the blocks overlying the great thrust-planes are slowly retreating, the first principal valley is that occupied by Waterton lake and Mineral creek in Montana. As stated by Willis, this valley seems to be constructional in the sense that it occupies the floor of the wide syncline forming the twin Clarke and Lewis ranges.* The two ranges are separated by this valley.

The Clarke and MacDonald ranges are separated by the wide Flathead valley which is a 'graben,' or trough bounded on both sides by normal faults. Since the Kishenehn formation is, so far as known, rigorously confined to the trough, the principal faulting is to be referred to early Miocene or pre-Miocene time. Ever since, the graben seems to have existed as an actual topographic depression, though some deformation of the fresh-water beds flooring the trough has taken place in late Miocene or still later time. This latter fact has led Willis to suggest a Miocene or possibly Pliocene date for the principal

* B. Willis, Bull. Geol. Soc., America, Vol. 13, 1902, page 347 and Plate 53.

faulting.† His view, however, gives no explanation of the strictly local character of the Miocene beds. The observed deformation of the clays can be explained by the late Miocene lateral pressure which affected the Cordillera in this latitude.

The Rocky Mountain Trench and the Purcell Trench are likewise located on zones of profound faulting; in each case the constructional profiles may have been those of grabens as typical as that of the middle Rhine or that of the Dead Sea. The dating of these faults cannot be made with assurance but the resemblance of the present topographic relations of fault-planes and retreating escarpments to the same relations at the Flathead suggests that in all three instances, the faulting was post-Laramie and pre-Miocene. In the two trenches there is no evidence of their having been floored with Tertiary sediments. The absence of such sediments is most simply, though of course not surely, explained by the hypothesis that the trenches have undergone erosion ever since their formation. Each of them has been much widened and deepened by erosion; considering the hardness of the rocks it is not incredible that all of late Miocene and post-Miocene time has been occupied with that task of excavation.

We have seen that the Christina lake valley is probably located on a meridional fault of considerable, perhaps very great throw. The Pasayten valley may be due to excavation along the outcrop of the relatively weak Pasayten Volcanic formation, and, if so, may possibly be classed among the subsequent valleys developed by adjustments to soft belts of rock. The Skagit river valley is located on a zone of strong faulting, which at the Forty-ninth Parallel separates the Hozomeen range from the Skagit range.

On the other hand, several of the master valleys in the section have no direct explanation in the visible structures of the terranes over which the respective rivers flow. The Columbia river in the Selkirk Valley has been 'superposed,' through a complex of volcanic and stratified rocks, upon the Trail batholith or upon the chaotic Pend D'Oreille schists lying unconformably beneath the lavas and younger sediments of the Rossland group. This part of the Columbia valley can, with much confidence, be referred to a post-Laramie and pre-Glacial date; we have no facts compelling a closer dating within that long period. Nor is it yet possible to choose between the hypothesis that the river is here consequent on the relief initiated during the Laramide orogenic revolution, and the hypothesis that it has been located by some subsequent adjustment to a soft belt in the roof of the Trail batholith. A like problem and a like uncertainty prevail in the case of the great Okanagan valley, a part of which separates the Okanagan range from the Belt of Interior Plateaus. The lower Fraser river valley, as well as the lower Chilliwack valley may be located on the axes of east-west folds which here seem to be unusually common in the Cordillera; the poor rock-exposures do not give data sufficient to establish this view finally. The upper Chilliwack river has been superposed on the Chilliwack batholith through a cover of folded Paleozoics.

† B. Willis, ibid., p. 344.

Lower Okanagan Valley and Osoyoos Lake; looking southeast down the valley.

Looking southeast across Starvation Creek canyon. Serrate ridge chiefly composed of Siyeh formation.

Individual Mountain-Ranges as Physiographic Provinces.

Corresponding to these genetic explanations of the master-valleys, so far as they can now be made, the intervening mountain-ranges can be considered as forming fairly definite structural units.

The Clarke-Lewis mountain group is made up of a locally warped and broken synclinal block which is in overthrust relation to the Great Plains on the east, and in what may be called 'horst' relation to the block underneath the Flathead valley. Following Suess, a 'horst' may be defined as a crustal block which stands in relief because it is bounded by lateral normal faults.

Then, in order from east to west, we have the following physiographic units which together make up most of the Cordillera at the Forty-ninth Parallel:

Ranges.	*Physiographic Provinces.*
Rocky Mountain System	The Front Range syncline. The Galton-MacDonald horst.
Purcell Mountain System	The Purcell horst.
Selkirk Mountain System	The Selkirk monocline.
Columbia Mountain System	The Rossland-Phoenix volcanic cap. The Midway volcanic cap.
Belt of Interior Plateaus	The Anarchist old-mountain plateau.
Okanagan Range	The Okanagan composite batholith.
Hozomeen Range	The Pasayten monocline. The Hozomeen horst (including merely the ridge of Mount Hozomeen.)
Skagit Range	The Skagit volcanic cap. The Skagit composite batholith (including the Custer, Chilliwack and Slesse plutonic bodies). The Chilliwack province of folded Paleozoic sediments.
	The Gulf of Georgia (Puget Sound) down-warp.
Vancouver Range	The Vancouver complex.

Front Range Syncline.—The Clarke and Lewis ranges furnish the most interesting scenery on the whole Cordilleran section; in this respect their only possible competitor is the Cascade range in the extreme west. Fortunately we have the quality of the eastern ranges admirably portrayed in the 'Chief Mountain Quadrangle' sheet of the United States Geological Survey (topography by F. E. Matthes and R. H. Sargent, 1900-1902). A part of each of the two Front ranges is mapped within the quadrangle; the map may be profitably consulted by one who wishes to appreciate the full individuality of these mountains as compared with the ranges west of the Flathead.

The relief is considerable. Waterton lake is given as 4,186 feet above sea, about the altitude of the Great Plains in this latitude. The Flathead is about 4,000 feet above sea. Cleveland mountain in the Lewis range and six miles south of the International line, is given as 10,438 feet in height. Within the Boundary belt itself two of the highest summits are Mt. Thompson (9,926 feet) and Starvation Peak (9,300 feet). A total range of over 6,000 feet is registered in the vertical relief; the mountain slopes generally run from 3,000 to 5,000 feet in height.

Much of the interest of the scenery is due to the architectural effects, which in turn are controlled by the bedded structure of both ranges. The constituent rocks belong to the most heterogeneous part of the Rocky Mountain Geosynclinal; strong and weak beds alternate very often through the series and advanced erosion has brought out the familiar repetition of scarp and talus. The dips of the strata are generally low, so that the appearance of coursed masonry in infinitely varied design characterizes these ranges. Most of the summits are well above tree-line (7,200 to 7,500 feet), whereby the profiles of the many retreating escarpments are kept sharper than they would be under such a heavy forest-cap as that mantling the more westerly ranges. A yet more powerful influence in fashioning the truly magnificent peaks, precipices and savage, serrate ridges is the local glaciation which, as noted in the foregoing chapter, has been so important in the Front ranges. The development of the hundreds of beautiful cirques has, however, been greatly aided by the heterogeneity and the structure of the sedimentary rocks in which cirque and basin have been excavated. It appears probable that the head-wall recession, with consequent formation of the steepest cliffs in the region, has been specially hastened through the natural blocking of the strata by joints and bedding-planes; such structures must have aided the frost in quarrying along the schrund-lines of the many local glaciers. The sharpening of the profiles through the work of the Pleistocene cirque-glaciers is well illustrated in such views as that in Plate 9. Similar contrasts between the pre-Glacial topography and that directly caused by head-wall recession are shown in the Wasatch, Uinta, and Big Horn ranges of the United States.*

Notwithstanding the intensity of Glacial erosion in the Clarke-Lewis mountain group, the major topographic features are, as usual in large ranges, of pre-Glacial origin and have been caused by crustal movement and normal stream erosion. The relatively simple structure of the mountain group—synclinal with minor arches and faults developed in both ranges—suggests a comparatively simple origin for some of the streams and valleys. The Mineral Creek-Waterton River valley has already been described as apparently consequent in origin, the stream flowing along the axis of the syncline. Akamina creek, which is followed by the South Kootenay Pass trail, is located in the bottom of a minor synclinal roll in the midst of the master syncline, and may also be of direct consequent origin. Kishenehn and Starvation creeks are examples of just such stream courses as we should expect to have been formed on the eastern slope of the Flathead fault-trough, in consequence of that graben-sinking. Many other roughly parallel creeks and canyons on this slope of the Clarke range may likewise be classified as probably consequent in origin. Kintla creek is located on a distinct fault which may have been the line of an actual depression in the original deformation of the Lewis series of sediments; if so, this creek and its canyon are consequent. Yet we can hardly exclude the possibility that the fault-zone has functioned as a natural weak

* See the recent monograph by W. W. Attwood on the Uinta and Wasatch Mountains, Prof. Paper No. 61, U.S. Geol. Survey, 1909; especially Plates 4 and 8.

place in the range, along which the Kintla canyon, as a subsequent feature, has been slowly developed. The unnamed lake just east of the monument on the Great Divide, together with the outflowing creek, occupies a short valley which seems to have a consequent course down the northeastern slope of the minor anticline at the summit. On the other hand, Cameron Falls Brook (Oil creek) in its lower part (below the sharp elbow) is clearly located in the heart of a similar, narrow anticlinal roll and has the relation of a subsequent stream. Subsequent streams, that is, those which are adjusted to soft rock-belts, seem, however, to be very rare both in the Boundary belt and in the finely mapped areas covered by the Kintla Lakes and Chief Mountain quadrangles of the United States Geological Survey. True obsequent drainage is necessarily limited in the same proportion.

The numerous lakes of the ranges are of Glacial or post-Glacial origin. Lower Kintla lake has been formed by a dam of morainal material, though it is possible that a true rock-basin also exists beneath its surface. Soundings of over 300 feet are reported in this lake. Upper Kintla lake is partly or altogether due to damming by a strong alluvial fan flung out across the canyon from the south. Many other small lakes of the ranges are true rock-basins and, as such, have been discussed briefly in the preceding chapter.

For a brief account of the relation of topography and structure in the Lewis range, the reader is referred to Willis's often quoted paper of 1902.* He points out that, as in the Clarke range, the main syncline is accidented by at least one narrow anticlinal fold. He has followed this fold from Mt. Cleveland southward to Mt. Gould. The former peak is the highest in the range and Willis shows that the greater heights are coincident with the axis of this arch, implying a 'general relation of mountain belt to anticlinal zone.'

He writes further: 'In northern Lewis range and in Livingston [Clarke] range greatest altitudes are in general related to anticlines.' It should be observed, however, that the Mount Cleveland anticline and, as well, a similarly narrow one at the summit monument in the Clarke range, are merely local rolls in the floor of the master syncline, so that we may also hold that the greater heights are related to a general synclinal axis.

Like the present writer, Willis was unable to find many examples of possible stream adjustment in either of the two ranges, and there seems to be no doubt that most of the streams in the region have really consequent courses. This conclusion is of moment in view of the fact that each range is composed of rocks of very considerable differences in strength. Such heterogeneity would almost certainly involve much more adjustment of the streams to soft belts than we actually discern, if the region had ever been reduced to the condition of a peneplain. Yet this is the definite view reached by Willis as a result of his studies during 1901. Its discussion may well be postponed until a short description is given of the physiographic features of the Galton-MacDonald mountain group, for Willis holds that that group was peneplained during the same erosion cycle.

* B. Willis. Bull. Geol. Soc. America, Vol. 13, p. 346.

Galton-MacDonald Horst.—Between the Flathead and Gateway-Kootenay grabens we have the compound horst which may with advantage be considered as a physiographic unit, though it is topographically divisible into the Galton and MacDonald mountain ranges.

The relief is not so great as in the Front ranges. On the east the local baselevel is given by the Flathead river at about 4,000 feet; on the west, by the Kootenay at about 2,300 feet. The highest summit of the MacDonald range in the Boundary belt is 7,724 feet high. The highest summit of the Galtons in the belt is 7,930 feet. Most of the ridges in each range average about 7,000 feet in height. Comparatively few of them are above tree-line, which is at elevations, varying locally with the nature and exposure of the slopes, of from 7,300 to 7,700 feet.

The quality of the topography is also contrasted with that of the Clarke and Lewis ranges. Though the rock-formations belong to the same horizons as there, forming simply a more westerly phase of the Rocky Mountain Geosynclinal, the beds are distinctly less heterogeneous and seldom show the cliff and talus form even where the beds lie flat. The Purcell Lava is almost the only member which preserves the cliff-making property, though the massive Siyeh formation tends to form specially steep slopes on its outcropping edges. The mountains of each range make up a rather rugged assemblage of ridges crowned by occasional low horns, but the true precipice is seldom seen. The reason for this is double; partly due to the softening effects of the general forest-cover, partly to the relative weakness of the Pleistocene local glaciation as compared with that across the Flathead. Steep as many of the ridge slopes are, they are those of graded profiles in a maturely dissected mountain-range. The grading was pre-Glacial and the associated veneer of creeping rock-waste was largely removed during the general glaciation of these ranges.

Within the horst itself the relief is clearly due for the most part to normal stream erosion, acting on a number of fault-blocks. The explanation of the topography is, therefore, at hand, as in the case of the Front ranges, if we can arrive at final conclusions as to the origin of the streams and their valleys. Again we are baffled in reaching that desirable end, and most suggestions are subject to doubt until much further field-work has been accomplished. It would, however, seem probable that the narrow Boundary belt offers an average sample of the topography for the whole mountain group and its indications are not without value. We have already seen that the Flathead and Kootenay are respectively located on fault-troughs and may, therefore, be classed as consequent rivers; as they run parallel to the Cordilleran axis we may further describe them as longitudinal consequents. The Wigwam river seems to be located on a master fault, though not on a well-defined graben. Analogous relations are observed among some of the branches of the Wigwam in the Boundary belt. (See map.) Most of the other creeks and canyons of the group have no discernible relation to rock structures like faults or folds; the larger transverse streams appear to represent consequents draining the compound horst to east and west on the constructional fault slopes, but they have gnawed well back into the now well dissected fault-blocks. The lack of adjusted drainage may be partly explained by the relatively small differences of strength in the bedded rocks, but one must suspect that it is also due to the fact that time enough has not been given for a thorough searching out of soft belts by head-water branches. The Carboniferous limestone seems to be distinctly softer than the neighbouring silicious rocks of the Galton series and depressions are begun in the limestone.

QUESTION OF A TERTIARY PENEPLAIN IN THE ROCKY MOUNTAIN SYSTEM.

Willis's many-sided, interesting paper contains a clear statement as to the view that the whole Rocky Mountain system from the Rocky Mountain Trench to the Plains, was peneplained in mid-Tertiary time. If this be true, any scientific description of these ranges should be phrased in terms of that fact, just as description of the Appalachians is made at once more simple and more true by assuming the Cretaceous peneplanation of that eastern mountain chain as an event of primary importance. The virtue of the conception is great, for it clarifies both the geological history and the topographic description of the Appalachians in an unequalled manner.

Unfortunately, the present writer has been unable to accept the hypothesis because of certain grave difficulties which are not felt in the case of the hypothesis of peneplanation in the Appalachians. A brief digression may fitly be made to traverse the problem before proceeding with the notes on he physiography of the Purcell system.

To present the case as outlined by Willis, it will be well to quote at some length but the reader should consult the original paper in order to appreciate the whole of the argument. On pages 344-349 we read:—

> 'Recognition of the tilted attitude of Cretaceous strata and of the even surface extended across their edges is sufficient to demonstrate the character of the Great Plains, at least in the belt adjacent to the Front ranges. The surface is one of planation, independent of structure, and, marine planation being excluded on strong negative grounds, it may be considered a peneplain. Several stages of erosion may be noted in the relief of the Great plains, but the one here referred to is that which is represented by the highest levels and which is the oldest. In the preceding discussion of antecedents of the Lewis thrust [page 92 of this report] it was named Blackfoot peneplain and assigned to a pre-Miocene cycle of erosion. . . . . .
>
> 'The rise of the Lewis range above the Blackfoot plain is more than is reasonably attributed to difference of hardness of rocks. Limestones and quartzites could not have maintained such relative altitude so near a lowland in which shale and sandstone were reduced to a plain. The later forms sculptured in the Blackfoot plain are apparently represented by equivalent features in the Front ranges. When their correlation has been worked out, remnants of a surface may be recognized as belonging to the Blackfoot cycle in old age. They may be traced among high shoulders of the peaks, which must then be considered monadnocks, or they may be

the tops of peaks. In the latter case the surface may appear closely to conform to the highest summits of the crests and to lie above the structural valleys. . . . .

'The Front ranges are distinguished from physiographic districts adjacent to them by the dominant influence of structure on altitude described in the preceding paragraphs. In strong contrast, the Great Plains exhibit features of erosion entirely independent of structure. Galton range, though as a mass bounded by structural limits, is within itself apparently a simple uplifted block. Whatever minor flexures or faults may exist near the 49th parallel they are not sufficiently pronounced to interrupt the unity of the mountain mass. While the general altitude of 7,500 feet is due to uplift, details of heights express effects of earlier or later erosion only. In this respect Galton range is like the Plains and unlike the Front ranges.

'On the Plains and over Galton range a peneplain was developed. On the soft rocks of the Plains it was planed flat. On the harder rocks of the Galton mass it was probably not so completely smoothed. Observations of 1901 were neither so extensive nor so precise as to distinguish monadnocks from features of later carving, but the general relation of height to an old lowland is as distinct as it is on the Schooley plain, in the Highlands of the Hudson, New York. The peneplain on the Great Plains, the Blackfoot plain, is neither incidental nor local. It is the result of a long cycle of erosion, which affected a wide territory, and its representative must occur in the nearby mountains among the oldest features, if not as the oldest, unless it has been obliterated by later activities. A tentative correlation of the Blackfoot plain with the peneplain over Galton range is a reasonable inference from these facts. Nevertheless, in the intervening Front ranges the observer seeks in vain for that general uniformity of altitudes or that breadth of contour which might represent the Blackfoot plain.

'The peculiarly bold sculpture of the Front ranges is explicable, offhand, as an effect of great elevation, from which there resulted special conditions of glaciation and erosion. It resembles the sculpture of the Cascade range, Washington, as nearly as is consistent with diversity of rock-types. But unlike the Cascades, whose summits inherit common altitudes from a broad peneplain, the Front ranges exhibit no general upper limit of heights common to many widely distributed peaks. Instead, they present an extreme case of localized deformation, accentuated by intense corrasion. Realizing this, one may still recognize the position of the oldest topographic surface of the province near the summits of the ranges. It is notable that each peak approaches in height those of its neighbours which stand in similar structural positions—that is, along the strike. A surface restored over the peaks, or over their wider shoulders, should represent that from which they are carved, plus or minus the effects of warping and minus the effects of later erosion. Detailed observations of structure will determine the former; studies of stratigraphy in relation to sculpture will evaluate the amount by which erosion has reduced altitudes relatively on the several rock types—argillite, limestone, quartzite and diorite. The determinations may be checked on some surviving areas of ancient relief. When existing profiles have been raised or lowered in accordance with these values, there will result a surface, which, in the writer's judgment, will closely correspond with the peneplain over Galton range. The conclusion involves elements which the eye cannot rightly estimate in the field and for which precise data are not at hand. For this reason the writer is disinclined definitely to place the peneplain relatively to the heights of the Front ranges; but, recognizing the insignificant extent of summit areas, or of shoulders that might support modified monadnocks, he thinks it may be located on top of the highest peaks rather than below them.'*

Combining the conceptions which are embodied in the quotation with others contained in the body of Willis's paper, we may tabulate his hypothesis as to the origin of the existing relief of the Front ranges, as follows:—

1. The 'Algonkian' strata were reduced to a peneplain in early Cretaceous time. This old erosion surface subsided beneath the Benton sea, which extended as far west as about the longitude of Waterton lake.

2. During Dakota and Benton time there was a very gentle and broad upwarp of the Front ranges area, accompanied by sedimentation in a sea which covered only the eastern part of the belt now occupied by the Lewis range.

3. At the close of the Laramie (presumably at the time of the general Laramide revolution) there was a single upwarp of the 'Algonkian' and overlying Cretaceous beds, forming an unsymmetric fold with steeper dip on the east.

4. During the early Tertiary a long period of crustal repose during which the upturned rocks were all more or less perfectly planed and the Blackfoot erosion cycle completed. The peneplain was most perfect on the soft Cretaceous rocks, but there was probably 'low, hilly, post-mature relief on the Algonkian [Lewis series] rocks.'

5. In the mid-Tertiary the great Lewis overthrust took place, whereby the greatly eroded 'Algonkian' block of the Front ranges and the equally broad mass of the Galton-MacDonald group were uplifted.

6. Apart from local normal faulting, the subsequent history of the region has consisted in steady erosion, leading to mature mountain topography.

In passing, it may be noted that the evidence of the earlier Mesozoic peneplain on which the Dakota and later Cretaceous beds were deposited, is not made clear. It would seem probable that during the Mesozoic, this part of the Cordillera was never far above sealevel. Most of the Mississippian limestone formation is still preserved in the Crowsnest district only fifty miles to the northward on the strike of the range. To the southeast its equivalent is likewise preserved beneath the Cretaceous beds of the Belt mountains. We have

* B. Willis, Bull. Geol. Soc., America, Vol. 13, 1902, pp. 344-349.

seen that a great thickness of the Mississippian limestone persists in the fault-blocks of the MacDonald range just across the Flathead. Nowhere in the eastern part of the Cordillera north of Colorado is there evidence of notable deformation of the Rocky Mountain Geosynclinal between Mississippian and Laramie times. It seems likely, therefore, that a great thickness of the Mississippian limestone was present in the MacDonald range area before the Laramide or post-Laramie faulting dropped the large masses of the limestone into lateral contact with the Altyn formation of the MacDonald range. If this be granted, it follows that little erosion had been accomplished by erosion in this latitude during the Mesozoic. The Mesozoic erosion-cycle could not have very great significance in the region.

Returning to the main theme, we may note that Willis's evidences for the mid-Tertiary peneplanation are: (*a*) the truncation of the crumpled Cretaceous; (*b*) the presence of accordant levels among the summits of the Galton-MacDonald mountain group. Concerning the first point, it is not made certain that the truncation of the Cretaceous was observed outside the area which may reasonably be supposed to have been overridden by the overthrust block of the Front ranges. This thrust, as shown at Chief mountain very clearly, has not only crumpled the Cretaceous beds but has sheared them off sharply at the plane of the Lewis thrust. In some measure the observed truncation elsewhere may be attributed to this constructional process, for there is clear evidence that the original eastern edge of the overthrust block lay several miles to the eastward of the existing frontal escarpments of the Lewis and Clarke ranges. Of course, erosion has modified the surface of scission thus exposed by the retreat of the escarpments, but its base-levelling effect must here have been vastly inferior to that which was demanded on the hard quartzites and silicious dolomites of the Lewis series.

The argument from the accordance of summit levels cannot, in the writer's opinion, be safely applied in any one of the four ranges now in discussion. In no one of them is there any notable remnant plateau which can fairly be said to prove general baselevelling in a former erosion cycle. The writer has already published the grounds of his protest against using the accordance of peaks and ridges as an evidence of two erosion cycles; a full abstract of that publication will be given at the close of this chapter, to which the reader may turn. In brief, the point is made that sub-equality of heights is to be expected from the early stage in the history of every alpine mountain range.

The evidences against the hypothesis of a mid-Tertiary peneplain on the Front ranges seem to be powerful. First, the time allowed is not sufficient for peneplanation or even past-mature development, followed by uplift and mature dissection in a second cycle. All post-Cretaceous time has not been enough to destroy the large monadnocks on the well-established Cretaceous peneplain of the Appalachians, though their rocks are not sensibly stronger than those of the Front ranges of the Cordillera. In most of the Appalachian belt a very large percentage of all Tertiary time has sufficed to do no more than form mature or submature topography through the dissection of the generally well elevated Cretaceous peneplain. Yet the climatic and other erosion conditions are not now very different, and probably have not been very different, in the two mountain-chains throughout the Tertiary. It seems, therefore, hard to believe that the exceptionally tough rocks of the Front ranges at the Forty-ninth Parallel have been peneplained once and maturely dissected afterwards since the close of the Laramie period.

Again, the general lack of stream adjustment in the entire section from the Great Plains to the Flathead trough is a valid reason for rejecting the two-cycle hypothesis. Difficult as it is to be sure in the case, it seems that most of the drainage is of consequent origin. Contrast with this condition that of the middle Appalachians, where subsequent drainage is probably dominant over all other kinds of drainage! In this region of two cycles there has been time enough for head-waters to lengthen the streams by gnawing back into the soft belts for even scores of miles. Yet the second important cycle is still not past maturity. Well-developed subsequent drainage is the rule in many parts of the Appalachians where the rocks are all hard in an absolute sense, though differing relatively in power to resist erosion. In the Front ranges of the Cordillera the rocks are all strong but he is bold who would deny that some are notably weaker than others and should thus ultimately guide headward growth of streams in a two-cycle period of time. Failing such manifest guidance along the strike of certain beds of the Lewis series, it must be said that this well recognized criterion of multiple cycles (so justly emphasized by Davis and others) does not favour the idea of a mid-Tertiary peneplain in the Front ranges.

Finally, the one-cycle hypothesis, whereby only one major episode of deformation (the Laramide) and one erosion-cycle (including all of Tertiary time) are postulated, seems competent to explain the present topography.

The accordance of summit levels is here partly implied in the relatively small degree of deformation other than uplift; for the rest, it is explicable on the composite hypothesis discussed at the close of the chapter.

The bevelled surface of the Cretaceous may truly mean a widespread peneplain on the soft rocks of the Great Plains, but it by no means implies a peneplain on the much harder rocks of the Front ranges. The erosion of both provinces has been chiefly occasioned by rivers and creeks issuing from the mountains. In the mountains these streams have high gradients but small volume; outside the mountains, tolerably swift currents and much greater volume. It seems necessary to believe that on the plains these streams would, through lateral corrasion, develop a peneplained surface with relative rapidity. In the mountains the threads of water must develop such a surface from rocks like those of the Lewis series, with immense slowness. Willis's argument that it is unlikely that the peneplain formed on the Cretaceous of the plains should not adjoin a rugged, scarped mountain range of contemporaneous development seems to be a very doubtful one, in view of the fact that the precisely similar relation is seen in the case of the dissected Niagara escarpment overlooking the Tertiary lowland of New York and Ontario. Similarly, the Catskill escarpment overlooks the Tertiary lowland of the Hudson valley, and the crystalline terranes on each side of the Connecticut valley dominate the peneplained

Triassic sandstone of that valley. In these Appalachian cases we cannot doubt that the upper facets are of Cretaceous date, the lower peneplains of relatively late Tertiary date; that is, they have a great contrast of age, and one which is significantly like that suggested by the writer for the flat erosion-surface of the Great Plains and the adjacent blocks of the Front ranges. Furthermore the eastern slope of each Front range is generally a retreating escarpment and, as already noted, the retreat is to be measured by miles, perhaps by many miles in some places. The structure of the region, with soft underlying hard at the Lewis thrust, necessarily involves a steep retreating mountain-front so long as the thrust-plane remains above baselevel. The case is again analogous to the Catskill or Niagara escarpment except that in those cases the erosional undermining is controlled by bedding and not by a flat plane of overthrust.

Again, the dissection of the Front range blocks is just of the order of magnitude expected from the analogy of lithologically somewhat similar Appalachian terranes, which have been maturely dissected in a well dated erosion cycle occupying the larger part of Tertiary time.

Since the character of the drainage is apparently that to be expected on the one-cycle hypothesis for the region, it seems that all the essential topographic features are explained by that hypothesis. The writer believes that no proved structural relation in the bed-rocks needs the two-cycle hypothesis for its explanation. In conclusion, therefore, he would state his belief that the Front ranges, as well as the Galton-MacDonald group, were uplifted in the one episode of the Laramide orogenic revolution and have undergone steady erosion ever since, this erosion reaching maturity and no later stage. It is possible that a horizontal thrust has deformed the unconsolidated Miocene clays of the Flathead trough, but there is no clear evidence that this movement affected the great blocks to east and west in any essential way.

The argument has been dwelt upon not only because the physiographic history is also the geological history of the Rocky Mountains proper, but also because a similar history may be credited to the broad Purcell mountain system, to the brief discussion of which we may turn.

Purcell Compound Horst.—The relief of the Purcell system is indicated by the elevations of the local baselevels as compared with the highest summits. The Kootenay river at Gateway is about 2,300 feet above sea, and at Porthill, about 1,750 feet above sea. The highest peak in the Boundary belt between the two crossings of the river is mapped as 7,518 feet in height.

This broad, compound horst is throughout composed of exceedingly strong rocks, chiefly quartzites, though the thick sills of gabbro are perhaps somewhat stronger than the quartzites, and the Purcell Lava is certainly stronger than the associated metargillites. The lava makes strong scarps on the limbs of the broad syncline of the McGillivray range and forms a strong ridge on the eastern limb of the anticlinal fold just where the stratified series plunges under the surface deposits of the Rocky Mountain Trench. Another hint at differential hardness is found in the development of the steep escarpment facing the Moyie sills, and it is possible that the steepness of the McKim cliff is partly due to the thick intrusive sheet of gabbro toward the top of the cliff. As a rule, however, the uniformity of the rocks in strength is almost as striking as it is in great batholiths of granite and that strength is nearly of the same order of magnitude. Such variations in resistance to the weather as might have become manifest in the topography if these rocks had been exposed to erosion under arid conditions, are effectually obscured by the fact that the region has been for a long period covered with a heavy forest-cap, which, as usual, blunts the angles of relief whether in profile or ground-plan. For various reasons, therefore, this mountain system nowhere approaches the scenic quality of the Front ranges. The Purcell system is deeply canyoned but lacks the architectural effect of the more easterly ranges. It will be recalled that the Front ranges are composed of the much more heterogeneous rocks equivalent in age to the Purcell system quartzites.

The structure is essentially that of a series of fault-blocks, the McGillivray range alone showing true folds which themselves are broken by faults. The different blocks have been diversely moved so that the dips run from 0° to 90°, with an average of perhaps 40°. There is no evidence that the faulting belongs to more than one episode of deformation; this may most simply be referred to the Laramide revolution. It is very unlikely that any original fault-scarps are represented in the topography, which has been chiefly determined in details by profound erosion. The obvious difficulty of discovering the form of the constructional surface of this great compound horst makes it difficult to describe the stage of erosion represented by the usual terms of the erosion-cycle; but the degree of relief is about that found in maturely dissected plateaus or other physiographic units where the original form can be reconstructed. With the qualification just made we may profitably speak of this erosion, like that in the Front ranges, as mature.

The master streams of the region are located on fault-lines. Besides the two wide trenches at Gateway and Porthill, we have the West Fork of the Yahk river and the Moyie river located on either master faults or on zones of faulting. The subordinate valleys are in some instances placed over similar breaks. Among these may be mentioned the east-west valley mapped west of the McGillivray range summit and south of the Boundary; two meridional valleys occurring west of the West Fork of the Yahk; and the meridional valley immediately west of the Moyie river at the Boundary Line. As in the eastern ranges these valleys seem to be located on the lines of depression instituted at the time of faulting, but it cannot be said that they have not in some instances been developed by slow headward growth of streams which lengthened most readily along the relatively weak zones at the fault-planes. This subsequent origin is, however, not probable for the larger rivers. The zones of possible brecciation along the faults is almost certainly very narrow along most of the faults in the mountain system, generally not more than a few feet or scores of feet in width, if the outcrops are to be trusted. It seems therefore unlikely that wide master valleys would have been developed by stream adjustment to the fault-zones unless other and equally wide valleys had been simultaneously formed through streams adjusted to the softer, metargillitic members of the sedimentary rocks. Subsequent streams of the latter class are strikingly rare throughout the mountain system.

The drainage on the eastern slope of the McGillivray range has the look of consequent streams such as would be initially developed on the long eastern limb of the broad anticline in that part of the section. Similarly, a consequent origin is most plausibly attributed to the north-flowing creek draining the north-pitching axis of the syncline just west of the McGillivray summit. The main fork of the Yahk river is located in an anticlinal belt and it may represent a subsequent stream in this part of its course.

In summary, it may be said that the existing drainage of the Purcells has the relations of a set of dominant consequent streams and that there is little evidence of stream adjustment in this mountain system.

Each of the three constituent ranges shows the accordance of summit levels in a very notable way. In no case, however, is there any known remnant plateau of an old, uplifted peneplain. The problem of explaining the accordance of summit levels is the same as in the Galton range and, in fact, throughout the majority of the ranges crossed by the Forty-ninth Parallel, we have the same phenomenon. The problem's solution in terms of one erosion-cycle has already been partly indicated and will be discussed more fully on later pages.

Nelson Range Monocline.—The relief of the Selkirks at the Forty-ninth Parallel is given by the following figures. The local baselevels are the Kootenay river (at Porthill) with an altitude above sea of about 1,750 feet; and the Salmon river, at about 2,000 feet above sea. The individual mountains have elevations generally well under 7,800 feet, with Mt. Ripple (7,681 feet) as the highest in the Boundary belt.

Again the quality of the topography is that of 'mature' dissection in a strongly mountain-built region. The structure is chiefly that of a huge monocline of conformable strata, steeply upturned, with the exposure of a large area of its foundation, the Priest River terrane. The local uncovering of large batholiths of granitic rock adds an element new to our physiographic section but henceforth to be considered at intervals all the way to the Pacific. The generally very high dips together with the great thickness of the monocline lead to the anticipation of decided differences of strength in the different members; all of these may contrast in 'hardness' with the batholithic rocks and with the Priest River terrane which is itself heterogeneous. Field work justifies this view. All the rocks are strong in absolute measure, but there is clear evidence of important differences of strength among the many rock-formations. Among the more resistant members are the Ripple quartzite, the Wolf grit, and the Bayonne granodiorite. The weaker rocks include the Pend D'Oreille schists, the Irene conglomerate, and the many zones of metargillite in the Summit series.

The bold and fretted ridges and peaks of the range afford the finest scenery to be found in the Boundary section between the Clarke range and the Hozomeen range. The explanation of its impressiveness lies partly in the structure of the rocks and the nature of the erosion, but one cannot resist the suggestion that it may also be conditioned by the unexampled amount of orogenic uplift in this part of the trans-Cordilleran belt.

The drainage is chiefly transverse and directed into the Kootenay on the one side and the Salmon-Pend D'Oreille system on the other. Boundary, Corn, Summit, Monk, Lost, and Sheep creeks flow in canyons which may reasonably be attributed to streams which initially drained the great monocline—consequent streams. Notwithstanding the great variety of strength in the different rock formations, there is, here too, little evidence of adjusted drainage. Upper Priest river, flowing along the contact of the relatively friable Irene conglomerate which is adjoined by the weak phyllites of the Priest River terrane, may represent a short subsequent valley. The course of the Salmon is not easily explicable but may be tentatively considered as locally determined by the break of slope at the eastern foot of the high volcanic pile of Beaver Mountain. The superposed drainage on the granites, including the extensive Bayonne batholith, is transverse and apparently for the most part on the sedimentary cover. The same relation is largely true of the drainage on the Priest River terrane which has been so largely stripped of the overlying Summit series of rocks.

In general, therefore, the physiographic development of the Nelson range is, to all appearance, parallel to that in the Purcell and Front range systems. The evidence for more than one important erosion cycle since the post-Laramie upturning is practically nil. Considering the enormous amount of erosive work represented in the actual dissection of the monoclinal mass, it would seem that all Tertiary time has been no more than sufficient for the one erosion-cycle carried to the present stage of 'maturity.'

Bonnington-Rossland Mountain Group.—This field of relatively old, deformed volcanic rocks and of batholithic intrusives may be conveniently treated as a physiographic unit. Its local baselevel is the Columbia at about 1,350 feet above sea; the mountains are generally under 6,000 feet, with one notable peak, Old Glory mountain, reaching the height of 7,800 feet. With few exceptions the whole region is heavily forested.

This region may be described as somewhat past maturity of dissection. Horns are extremely rare; graded slopes are the rule, with contours and profiles generally well rounded. Nearly all of the Boundary belt has here been glaciated, with the resulting smoothing of angles under the ice-cap both by erosion and, in places, considerable deposition of a drift veneer. The ice-cap has, however, done little to affect the pre-Glacial, late-mature character of this torso landscape. The summits are relatively low here not only because the rocks have wasted somewhat more rapidly than in the more easterly ranges but more especially because the rocks of the Rossland district were not lifted nearly so high as those of the Nelson range at least.

The drainage history is largely undecipherable. The general arrangement of the streams suggests, however, the hypothesis that the original form of the thick Rossland volcanic pile controlled it in some measure, though consequent drainage down the slopes of the orographic blocks of Laramide date must have also been developed. Too little is known as to the bed-rock structure in the region to give certain clues on these questions. Western Sheep creek and the Christina lake valley are apparently located on meridional faults and may represent the erosion channels of consequent streams originally formed on the down-thrown blocks near the fault planes. The western two-thirds of the Coryell batholith is drained by streams in such courses as to suggest that this part of the drainage system is a direct result of the greater 'hardness' of the batholithic mass as compared with the country-rocks. That is, in this region the drainage once existing on the batholithic cover has been locally replaced by drainage which is centrifugal from the batholith because erosion has lowered the softer rocks all about. Such streams are not consequent on the initial relief of the batholithic cover but are consequent on the intrusion of the batholith, as well as subsequent to the beginning of the erosion cycle affecting the cover. To indicate the composite character of this kind of drainage the writer has proposed the adjective, 'subconsequent.'* The Coryell area does not furnish a very good case of subconsequent streams, in the sense that it is still difficult to prove such origin for them; yet there can be little doubt that the batholithic syenite is harder than the schists and volcanics round about. The course of the Columbia river at the Forty-ninth Parallel is an open problem. It is locally superposed on the Trail granodiorite but almost nothing is known which gives a detailed notion as to the origin of the valley in the batholithic roof.

Among the many physiographic details of these mountains only one will be here mentioned—the well known system of terraces of the Columbia valley. Simple as these gravel benches are in appearance, their complete history cannot yet be written. Much field-work needs to be done on each side of the Boundary and for hundreds of miles up and down the river, before the facts are sufficiently accumulated. For the present the writer will attempt to do no more than illustrate the most conspicuous terrace of sand and gravel where it occurs at the Boundary line (Plate 73, Figure A).

Christina Range and Boundary Creek District.—From Christina lake to the Kettle river valley at Midway, the relief and other physiographic features are much like those of the Rossland mountains, and again the systematic portrayal of these features, founded on genesis, has so far proved largely impracticable. The writer has made comparatively little personal study of this region in the field. The facts of relief are already well expressed for an unusual distance on both sides of the Boundary line. The difficult topography of the Boundary Creek District has been contoured with great fidelity by W. H. Boyd of the Canadian Geological Survey, this map serving as the basis for Brock's geological map of the district.† On the United States side we have the likewise excellent sheets of the Republic and Osoyoos quadrangles of the United States Geological Survey (1904). The topographic materials are, therefore, in hand for

* Geology of Ascutney Mountain, Vermont, Bull. U.S. Geol. Survey, No. 209, 1903, page 11.

† Publication No. 828 of the survey, 1905.

an unusually thorough treatment of the physiography in this part of the trans-Cordilleran belt. In his 1902 report Brock has given a short account of the district, but the physiographic study involves additional field-work before much can be written.*

Midway Volcanic District.—Excepting possibly the Anarchist plateau, the relief in the region about Midway is the least in the whole Boundary belt. The Kettle river at the town is about 1,900 feet above the sea and the mountains are seldom over 4,000 feet high. We are, in fact, approaching the Belt of Interior Plateaus. Between that belt and the more sharply accidented topography farther east, the Midway district is a transitional province.

The local topography shows considerable variation in character as it is followed through the areas of Paleozoic rocks, Tertiary volcanics, and Kettle River sediments. The first and third terranes are areally of little importance; the topography is that induced by erosion on a deformed mass of lava flows and pyroclastics of highly variable resistance to the weather. Glacial erosion is very subordinate in its effect of modifying the forms of the mountains, while Glacial drift veneers the slopes with depths which, for so large an area, are unmatched in the whole trans-Cordilleran section. The Boundary belt, from Record mountain ridge near Rossland to the higher summits of the Okanagan range was completely covered by the ice-cap of the Glacial period at the time of the maximum extension of the cap. The Forty-ninth Parallel is near the front of the slow, south-moving ice of that time; the reason is clear why the drift cover is thick and also why both ice and drift have occasioned many changes in the courses of the pre-Glacial lines of river flow. Some of these changes have been referred to in the preceding chapter. An important result of glaciation has thus been to obscure the physiographic history of the region even more than it would have been if it carried simply the record of events from the time of the Jurassic orogenic revolution to the dawn of the Glacial period.

Since the older rocks of the region have undergone severe deformation in the late Jurassic (if not at the close of the Pennsylvanian period), and in the period of the Laramide revolution, and since these and the Oligocene sediments and lavas of the Kettle River formation have suffered distinct deformation in a post-Oligocene period, it is almost or quite impossible to relate the drainage courses to constructional slopes. In this report no attempt is made to discuss the rivers and creeks from the genetic point of view. The same remark must be made concerning the streams now draining the plateaus on the west, where the problem is essentially as difficult.

The physiographer's attention will in this district, as in the plateaus, be attracted to details of land-forms and of erosional processes which, on account of the unforested character of much of the region, are conspicuously illustrated. A few of these cases may be mentioned.

The gravel and sand terraces of the Kettle river are in organic connection with those of the Columbia into which the former river flows. As the master

* See R. W. Brock, Ann. Rep. Geol. Survey of Canada, Vol. 15, 1902, p. 93A.

stream has sunk its channel into its own drift-filled valley-floor, the branch stream has been compelled to cut into the thick mass of washed detritus deposited in the Kettle valley in the late Glacial time. In the same way the affluents of the Kettle river, like Saw (or Baker) creek, have entrenched themselves in the local drift deposits. As is to be expected, the terraces so developed are proportioned in height to the size of the corresponding streams, so that the Kettle river benches are low when compared with those of the Columbia but are much more strongly developed than those of its own branches.

The formation of the Kettle river terraces has clearly followed the process generalized by Davis from the field relations of the similar terraces along the New England streams.* This process may be quickly understood from a study of Davis's papers on the subject. In this place let it suffice to say that the preservation of the terrace sands has been accomplished by the presence of 'defending' rock-spurs which the degrading, though meandering stream encounters at intervals, as it penetrates the loose material of the late-Glacial alluviation. The spurs inhibit the meandering of the stream; the width of the meander belt is thereby limited and the high-lying sands and gravels are safe from the river's attack until the much tougher rock-spurs have been destroyed as the result of much more prolonged lateral corrasion than post-Glacial time has yet allowed.

Several cases of truncated and compounded alluvial cones were observed in the Boundary belt. One of these is illustrated in Plate 65.

In this region for the first time we find two tree-lines, as Russell and other geologists have recorded in the dry country south of the Boundary. The upper line is determined chiefly by cold and drought. The lower line is determined by drought primarily. The forest is here, therefore, distributed only on intermediate slopes in the case of the highest mountains, like Mt. McKinney. Because of the low altitudes of most of the mountains, however, the lower tree-line only is generally visible in the Midway district. The height of this line is much more variable than even the normal upper tree-line. The exposure of the slope, the texture of the soil and rock beneath and yet other conditions must obviously affect the position of this tree-line at any locality.

Interior Plateaus.—The Anarchist old-mountain plateau merits its name although its general surface shows differences of elevation of as much as 1,300 feet. As a distinct unit with a culminating point of nearly 5,000 feet, it stands above the Okanagan valley which is about 930 feet above sea at the edge of Osoyoos lake. Practically the whole of the plateau is composed of greatly crumpled Paleozoic sediments and interbedded greenstones, except where these rocks are replaced by a part of the Osoyoos batholith.

Across the lake, and somewhat lower in altitude, is the Kruger-mountain plateau, composed of the same Paleozoic rocks together with various bodies of plutonic intrusives supposed to date all the way from the late Jurassic to the Miocene. The deep valley of the Similkameen separates the plateau from the Okanagan range.

So far as the field evidence goes, there is no reason to think that either of these massifs has been covered by sediments other than land-wash and Glacial

* W. M. Davis, American Journal of Science, Vol. 14, 1902, p. 77.

Compound alluvial cone at Midway. The terracing of the higher, older part of the cone and the building of the inner cone (still growing) represent a rhythmic process often observed in the Midway mountains.

drift, since the upturning of the late Jurassic. That is, we must recognize the probability that erosion has been actively at work upon the folded Paleozoics through all Cretaceous and Tertiary time. It is little wonder that the rocks show the effect of profound erosion or that the relief is that of a topographic torso. There has evidently been time enough for the completion of at least one full erosion-cycle in this region if the earth's crust had stood still. An obvious explanation of the plateau form of the massifs consists in the view that this region has been baselevelled at least once and has since been uplifted some 4,000 feet or more, whereby the deep Okanagan and Similkameen valleys have been entrenched beneath the old peneplained surface.

This is the hypothesis favoured by Dawson for the whole of what is here called the Belt of Interior Plateaus. His general statement may be quoted:—

> 'Chiefly because no deposits referable to the Eocene or earliest Tertiary have been found in this part of the Cordillera, it is assumed with probability that this was a time of denudation. It is further indicated that it was a time of stability in elevation, by the fact that the prolonged wearing down resulted, in the interior zone of the Cordillera, in the production of a great peneplain, the baselevel of which shows that the area affected stood 2,000 or 3,000 feet lower in relation to the sea than it now does, and that for a very long time. If, however, the Puget beds of the coast are correctly referred to the Eocene, it follows that the coast region was at the same period only slightly lower than at present, and that the movements in subsidence and elevation between this and the interior region must have been differential in character and very unequal in amount.'*

Dawson then describes the episode of Oligocene fresh-water sedimentation in the belt, followed by slight orogenic disturbances. These crustal movements are said not to have seriously injured the Eocene peneplain surface as a primary element in the Cordilleran topography. They were followed by a long continued period of volcanic action which covered much of the belt many thousands of feet deep with basic lavas and pyroclastics. These Miocene volcanics totalled 8,400 feet in thickness and another thousand feet of fresh-water sediments were intercalated in the volcanic series.† Even these additions to the belt are not credited with affecting the integrity of the 'Interior Plateau' as a peneplain, though it was locally warped or faulted during the late Miocene orogenic movement.

We may quote further:—

> 'Following the close of, or at least a great reduction in volcanic activity, in the early Pliocene, the interior zone of the Cordillera again assumed a condition of stability for a considerable time, during which wide and 'mature' stream valleys were formed. The elevation of the Interior plateau region of British Columbia must then have been about 2,000 feet less than it is at present . . . .

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* G. M. Dawson, Bull. Geol. Soc. America, Vol. 12, 1901, p. 89.

†These volcanics have recently been shown to be largely of Oligocene age.

'In the later Pliocene a very marked reëlevation of the Cordilleran region evidently occurred, leading to the renewed activity of river erosion, the cutting out of deep valleys and canyons, and the shaping of the surface to a form much like that held by it at the present day. This elevation in all probability affected the coast as well as the interior, and it would appear that the rivers for a time extended their courses to the edge of the continental plateau.' *

Dawson's statement as given and his more detailed accounts in the government reports on the belt show quite clearly that the accordance of levels among the many flat-topped massifs of the belt cannot be directly connected with the Eocene peneplanation. The same fact is at once apparent from an inspection of the Kamloops and Shuswap sheets of the Canadian Geological Survey. In those maps it is seen that a very large proportion of these typical areas of the belt is underlain by the nearly or quite horizontal post-Eocene volcanics, and that their structure alone amply explains the flatness of very many of the larger plateaus. This relation of surface to structure is like that explaining the flatness of the Columbia lava-field of the United States. Dawson's maps and reports show that the Eocene eroded surface must now, over large areas, be far below sealevel, while over other large areas the flat denudation-surface truncating the Triassic and Paleozoic terranes of the belt is more than 6,000 feet above sea. We may, therefore, safely exclude the view that the present accordance in the levels of the many plateaus in the belt is to be explained by pre-Miocene baselevelling. There are, however, plenty of local areas in the belt, as at Anarchist mountain, where the deformed Paleozoics are truncated by surfaces so flat as fairly to be called peneplains or extremely old mountains. For the enormous denudation there represented we have pre-Eocene time at our disposal in making explanation.

It seems clear, therefore, that, genetically speaking, we cannot call this part of the Cordillera, between the Coast range and the Columbia mountain system, a single plateau, unless it can be shown, in opposition to Dawson, that the accordance of summit levels among the different massifs is due to post-Miocene peneplanation. For this reason it is expedient to review the arguments of Russell, Willis, and Smith, who agree in advocating a Pliocene peneplanation in the Cascade range and on a great scale similar to that just suggested for the Belt of Interior Plateaus. The hypothesis of these United States geologists should, however, be considered in the light of the actual topography of the Okanagan, Hozomeen, and Skagit ranges. The further discussion of this matter of Tertiary peneplanation will, therefore, be postponed until we have made a brief study of the remaining ranges crossed by the Boundary belt.

Okanagan Range.—The local baselevels for the Okanagan range are found in the Similkameen at about 1,200 feet above sea and the Pasayten river at about 3,900 above sea. These streams occupy the valleys which respectively delimit

* G. M. Dawson, ibid., p. 90.

the range on the east and west sides. The higher summits in the Boundary belt include Snowy mountain with an altitude of 8,507 feet and Cathedral Peak with one of 8,610 feet. The range of the relief in a vertical sense is therefore relatively great.

The diversity of the relief is, however, all across the range, far less than it is in the Selkirk range on the east or in the Hozomeen and Skagit ranges on the west. Large areas of the Okanagan range are, in fact, plateau-like, strongly rolling, with frequent dome-shaped mountains surmounting the general surface by 1,000 feet or occasionally 2,000 feet. Snehumption creek has deeply canyoned the great mass on the eastern side, evidently because its master stream, the Similkameen, has been so successful in deepening its own gorge. Yet only some eight miles up stream the Snehumption is flowing at an altitude of 6,000 feet. For the next twenty miles farther west in the Boundary belt, the lowest points in the main valleys, namely, the forks of the Ashnola river, are respectively about 5,500, 4,900, 5,200, and 4,400 feet above sea. The next ten miles of the belt, being drained directly into the main Pasayten river, is naturally more deeply dissected. In all parts of the range the evidence is clear either that this range has had a different geological history from the greatly dissected Hozomeen range just across the Pasayten, or that the constituent rocks of the Okanagan range are much harder and have resisted erosion much more effectively than have the rocks of the western range. To the observer in the field both views are manifestly correct. Almost throughout, the Okanagan range is composed of exceedingly strong, granitic rocks; though the batholith is composite, its different members have about the same power of resistance to the weather. This composite batholith is, indeed, the largest terrane of nearly homogeneous rock-strength in the entire trans-Cordilleran section; the few small, schistose roof-pendants represent the only 'soft' rocks in the range as sampled in the Boundary belt. On the other hand, the Hozomeen range is heterogeneous in composition; sediments, relatively weak as compared with the granites, are there dominant and granitic rocks very subordinate. *A priori* it appears right to hold that this difference of hardness will chiefly explain the different degrees of dissection in the two ranges, and that there is no need to believe that the less dissected range has been lifted high above baselevel at a time later than that during which the more dissected range was raised.

Granting that conclusion, the leading question arises as to the cause of the plateau-like quality of the Okanagan range. Is its relatively flat upper surface the result of peneplanation close to baselevel, so that the deep valleys of the Similkameen and Pasayten rivers have been excavated as a result of an uplift of this Cordilleran block for 7,000 or more feet? Or can we explain the present topography in terms of one erosion-cycle, the flattish surface of the range being a spontaneous and necessary result of erosion in that one cycle? This second hypothesis may be coupled with the idea that minor changes of level may have taken place during the one cycle; the essential and highly important element wherein it differs from the first hypothesis consists in the fact that even imperfect peneplanation close to baselevel is excluded by the second hypothesis. Messrs. Smith and Calkins, who made a reconnaissance survey of the range in connection with the work of the International Boundary Commission, have preferred the first of these two hypotheses, while the present writer is practically forced to favour the second. To avoid repetition, the discussion of the alternative will be postponed until the two western ranges have been considered, for Smith and Calkins have extended the two-cycle hypothesis to the entire Cascade system, and it will be well briefly to review the facts before entering further into the field of theory.

There are many minor physiographic subjects of interest in connection with these beautiful mountains of the Okanagan range. The land-forms due to glaciation have been briefly treated in the last chapter. Certain physiographic processes unusually well illustrated in this range will be considered in the following general discussion of the erosion-cycles represented in the Cordillera. As regards the drainage it may here simply be said that, in this range, it is nearly all superposed through the roofs of batholiths. On a previous page it was noted that the Pasayten valley may be locally of subsequent nature, but there is doubt even of that one case, while elsewhere in the Boundary belt, there is practically no hint of adjustment. This feature, in a terrane so wonderfully homogeneous in rock-strength, is, of course, no argument against the two-cycle hypothesis. It is mentioned here, specially to show that the evidence as to the causes of the present stream-courses is extremely small. Beyond recognizing the fact of superposition through the batholithic cover, we can get almost no hint, within the Boundary belt, of this drainage history.

Hozomeen Range.—The main part of this range is composed of the great monocline of Cretaceous sediments, west of which is the narrow horst of the Hozomeen ridge. The local baselevels are found at the Pasayten with altitude of about 3,900 feet above sea and the Skagit at about 1,700 feet above the same datum level. The higher summits like Castle Peak at 8,340 feet, and Mt. Hozomeen at 8,020 feet above sealevel, are simply the culminating points on unusually high, steep-sided ridges. The canyons of this maturely dissected mountain-block range in depth from 2,000 feet to 3,500 feet or more. Glacial erosion has done something to sharpen the topography which locally bears true alpine horns, but the general cross-sections of the canyons are for the most part rather typical of water-stream and waste-stream erosion.

A glance at the geological map shows the fact, already recorded in earlier pages, that Lightning creek and the Skagit river locally follow the outcrops of master-faults. The same is true of the main fork of Chuchuwanten creek, and the parallel valleys immediately to the eastward seem to be located on another strike-fault. A few short, longitudinal branch-valleys draining into Lightning creek have the look of adjusted streams which have followed specially weak zones in the upturned Pasayten argillites. Most of the valleys in the Boundary belt are, however, transverse to the strike of the stratified formations. These valleys seem to represent the somewhat diminished successors of the consequent streams which originally drained the wide monocline and the adjacent horst respectively. Unless Lightning creek and the Skagit river are subsequent streams—which appears doubtful—, there is little stream-mileage in this part of the range which can be referred to the subsequent class. The recent unroofing of the Castle Peak stock has brought Castle creek locally into superposed relations. As erosion progresses it is practically certain that the surrounding shales will be lowered much faster than the granodiorite, whereby, in the end, Castle creek will probably lose its present head and the drainage of the stock will become 'subconsequent.'

Skagit Range.—The peaks of the Skagit range rival in height those of the Hozomeen range and the strength of the relief is yet greater, for the local baselevel, the Fraser river, is almost at sealevel. Sleese mountain at 7,800 feet, Glacier Peak at 9,000 feet, and many other ragged horns east and west of Chilliwack lake are ascended only after climbs of from 5,000 to 6,000 feet from Chilliwack lake or river.

The relief is again due chiefly to erosion, acting on the differential uplifts of an extremely complex mountain-built mass. This mass is heterogeneous, though its constituent rocks are generally strong in absolute measure; the relatively weak rocks are concentrated in the lower part of the western slope. Not a single constructional bed-rock slope is represented in the range at the Boundary belt, unless possibly the north-facing slope of the Skagit volcanic mass east of the divide is a fault-scarp of comparatively recent date.

Near the beginning of this chapter a suggestion is offered as to the difficulty of explaining the course of the Chilliwack river. Cultus lake valley, Tamihy creek, and the head-waters of the creek next on the west are located on master-faults, and, with further field-work, it may be proved that other drainage-lines have been similarly marked out by crustal breaks. How far the actual valleys were initially determined by these faults and how far they have been opened by headward growth of pre-Glacial streams which grew in length with relative rapidity along the rock-zones weakened by the faulting, it is still impossible to say. The genetic problem of the streams in this range is, in fact, here as in so many other of the ranges we have crossed, almost completely unsolved.

Some details concerning the important topographic features induced by the local glaciation have been given in the previous chapter, to which reference should be made for partial information regarding this phase of the physiography. Other features will be discussed in the succeeding section, which will deal in more general fashion with the Cascade mountain system as a whole.

Question of a General Tertiary Peneplain in the Cascade Mountains.

In the year 1900 Russell published an account of a reconnaissance in northern Washington, in which he announced the conclusion that the Cascade mountain system represents a late Tertiary peneplain upwarped and maturely dissected in late Pliocene and in Pleistocene time. He writes:—

'As described in an early portion of this paper, many peaks and ridges in the central portion of the Cascade mountains rise to a general uniform height of about 7,500 feet. If the present valleys could be filled to the level of the crests of the intervening ridges, the now excessively rugged mountain range would be transformed into a broad plateau. The structure of the rocks composing this plateau would find little, if any, expression in the surface topography. Many of the stratified beds would expose their edges and reveal the fact that they are the truncated bases of folds, and in many instances would stand vertical. In other words, if we accept the 'peneplain idea,' as elaborated by Davis and others, the surface of the plateau would be a plain such as is produced by base-level erosion. Briefly stated, the Cascade mountains as we now know them seem to have been carved from an upraised peneplain. This plain we term the Cascade peneplain, and the plateau may be conveniently designated the Cascade plateau.

'Rising above the general level of the Cascade Plateau there are two classes of peaks. First, volcanic mountains, of which Glacier Peak (near the 48th Parallel of latitude) is the only known representative in the region considered in this paper; and, second, granitic mountains, such as the Wenache mountains and the lofty peaks about Lake Chelan. The volcanic mountains stand on the Cascade Plateau and were formed after the period of base-leveling referred to above, and need not claim further attention at this time. Some of the granite peaks have an elevation of over 9,000 feet, and hence rise some 2,000 feet above the general level of the Cascade Plateau. These are the mountains which, in my opinion, could not have been in existence as topographic elevations at the time the main drainage lines were established.

'Possibly the granitic mountains referred to are of the nature of monadnocks, or remnants left standing on the Cascade peneplain. If this is true, the river courses which cross them may be explained as an inheritance from an earlier time of erosion which preceded the general base-leveling.

It may also be suggested in this same connection that the Cascade peneplain was developed above the present general summit elevation of the large majority of peaks and ridges now remaining, and has been lowered by erosion, leaving the more resistant rocks in the boldest relief. Under this supposition the Cascade Plateau would now have a general surface level of about 10,000 feet, having been raised from near sea level. In favour of this hypothesis it is to be noted that the peaks and ridges of the Cascade mountains are nearly all sharp. No recognizable flat-topped remnants of the original plateau remain in the more elevated portion of the region under review. As soon as a region has been so deeply dissected by streams that the ridges are sharp-crested, any further erosion will tend to a general lowering of their summits, and for a time they will continue to maintain this knife-edge characteristic. For this reason the Cascade Plateau, since being sculptured into a plexus of sharp-crested ridges, may have suffered a general diminution in height, owing to the wasting away of the ridges in soft rocks, while the hard rocks, presumably in this case the granites, retained more nearly their original elevation. It may be said in this connection that field observations do indicate that the granitic rocks of the Cascades are in general more resistant than the associated schists, serpentines, slates, etc. Again, the general level of the Cascade Plateau as it exists at present corresponds, approximately, with the timber line as determined by existing climatic conditions. As weathering is more active above timber line than below it, we have, perhaps, additional reason to assume that the Cascade peneplain, raised, as we have assumed, to a position about 10,000 feet above the sea, has in general been lowered to the horizon of the timber line, leaving the more resistant granitic rocks in relief. There are thus several arguments which it may be claimed tend to show that the surface of the Cascade Plateau was formerly higher than it is now and that it has been lowered by erosion, but to me the evidence seems far from conclusive.

'Another tentative explanation of the greater prominence of the granitic mountains over their neighbours of schist, etc., calls for local upheavals since the Cascade peneplain was raised into a plateau and subsequent to the initiation of the present master drainage lines. That is, if we assume that the granitic cores of the mountains have been pushed upward since the plateau was raised to its present general elevation of about 7,500 feet, all of the observed facts bearing on the question under discussion fall in line and find a mutual explanation.'

Russell was inclined to consider the latter hypothesis as the more probable one. After noting the evidences which are acknowledged not to be convincing, he proceeds:—

'Briefly stated, my conception of the origin of the larger topographic features of the northern Cascades is that the region, having a complex structure, was reduced by erosion to a condition of low relief and at a later time than the folding of the Tertiary sediment and the outspreading of the Columbia lava was broadly upraised about 7,500 feet in the axial region. The courses of the larger streams were then established and the plateau was deeply dissected. During this later cycle there have been movements in the rocks which, as a part of their results, have raised certain of the granitic areas above the general level of the plateau. . . .

'The date of the period of planation is shown approximately by the fact that folded beds of Eocene age were truncated. The broad peneplain must, therefore, have reached its greatest degree of perfection in late Tertiary time, probably extending into the Pleistocene.

'After the time of long-continued erosion referred to above, when the Cascade region in northern Washington was reduced to a peneplain, there came a time of elevation, when the peneplain, or a very large portion of it, was bodily raised some 7,500 feet at least, and thus became a plateau. In a broad view of the region this Cascade Plateau may be considered as of the nature of a broad, flat-topped anticline, or as Dana would probably have called it, a geanticline.'

Reasoning on this basis, Russell concludes that most of the larger streams of the Cascades, like the Skagit, Methow, Chelan, Yakima, etc., are of consequent origin. 'Their courses were determined, in the main at least, by the surface slopes of the Cascade peneplain.'*

Two years before Russell began his reconnaissance, Willis had come to very similar conceptions of the later geological history of the Cascades. These views were strengthened during several visits to the field between 1895 and 1900, inclusive. In collaboration with G. O. Smith, Willis published 'Contributions to the Geology of Washington,' in which the hypothesis of late Tertiary peneplanation was considerably amplified.† Again somewhat liberal quotations will be made, as this paper, like Russell's bears directly on the geology and physiography of the Forty-ninth Parallel in the Cascade system:—

> 'Among the services rendered the writer [Willis] by George Otis Smith was that of well maintained scepticism in regard to recognition of an ancient plain over the Cascades. He asked for demonstration, which was difficult, since the suggestions of panoramic views failed to convince, but during his field work of 1900 he himself supplied the evidence of an old base-level plain on the hills of Yakima valley, as stated in the first part of this paper.'

After giving an analysis of the topography in a large, typical area of the Cascades, Willis writes:—

> 'Enough has been said in the descriptions to indicate that several stages of topographic development have been recognized. They are clearly evident in such a profile as No. 1, Pl. XIX., from the Entiat mountains across Columbia canyon to Badger mountain. Beginning with the highest, the peaks (5,700 to 5,800 feet) and the flat adjacent to them are considered to be representatives of the oldest stage of which definite evidence remains. They are correlated with Badger mountain, the Waterville plateau, surfaces in the Chelan and possibly the Methow mountains, and the level from which the high Cascades are sculptured. This oldest stage is therefore that of the Cascade plateau, as named by Russell, but now called the Methow stage. It is also identified by G. O. Smith. The characteristic topographic type of the Methow stage was a plain, upon which residual hills survived. Following Davis, it may be designated a peneplain, with monadnocks.
>
> 'Within this plain were carved valleys which appear to have attained nearly mature development. That of the Columbia in profile No. 1, Pl. XIX., appears to have been 2,000 or 2,500 feet deep and seven or eight miles wide. The smaller streams certainly developed shallower and narrower valleys, but remnants of the Methow plain west of the Columbia were few and limited. On account of its preservation in the basin of the Entiat, this stage is named from that river. The characteristic topographic form

* I. C. Russell, Twentieth Annual Report, U. S. Geological Survey, Part 2, 1900, pp. 140-144.

† B. Willis, Prof. Paper No. 19, U.S. Geol. Survey, pp. 48 and 68-70.

of the Entiat stage is mature. It occurs as a spur or divide below occasional residuals of the Methow stage and above features of later stages.

'Within the relief of the Entiat stage there were cut deeper channels, some of them canyons of impressive depth, many of them simply mountain ravines. They constitute the most marked and everywhere the most characteristic features of the topography of the region. Any large stream might be chosen as exhibiting the type, but probably none shows it in various degrees better than the Twisp, which from its junction with the Methow to its source in the Cascades lies in a canyon that varies from a few hundred to 4,000 feet in depth, as can be seen on the Methow topographic atlas sheet. This stage is accordingly named Twisp. The characteristic of the Twisp stage is a canyon, the typical feature of topographic youth, but the development progressed far toward maturity.

'The Twisp stage closed with accumulations of glacial ice, which occupied the canyons and in many instances greatly modified them. . .

'It is somewhat difficult to place these several stages in geologic time. On the evidence of fossil plants from the Ellensburg formation, the Methow plain in the Yakima district is post-Miocene. The data are fully presented by G. O. Smith, and the unity of the feature throughout the Cascade range is discussed by the writer under its proper head below. The very long time required to accomplish such extensive and uniform leveling appears reasonably to occupy most of the Pliocene and to bring the date of the next stage near the close of that epoch. . . .

'The following tabulation expresses the most reasonable estimates of correlation for the several stages in geologic time:—

PHYSIOGRAPHIC DEVELOPMENT OF THE CASCADE RANGE.

Physiographic stage.	Type locality.	Nature of characteristic activity.	Date, if one uninterrupted Glacial epoch.	Date, if two or more Glacial epochs.	Period.
Stehekin.	Stehekin sources and valley.	Glacial retreat and re-excavation of old valleys.	Post-Glacial to present.	Post-Glacial to present.	Recent.
Chelan.	Gorge of Lake Chelan and terraces of the Columbia.	Glacial occupation of canyons.	Glacial epoch.	Latest Glacial epoch.	Pleistocene.
Twisp.	Canyon of the Twisp, Methow quadrangle.	General acceleration of corrasion.	Pre-Glacial.	Inter-Glacial.	
Entiat.	Basin of the Entiat.	Development of mature topography generally throughout the Cascade plateau.	Pre-Glacial.	Earlier Glacial epoch.	Pliocene or Pleistocene (Sierran Age).
Methow.	Generally throughout the broad mountain district.	Planation by erosion to a low plain with monadnocks.	Pre-Glacial.	Pre-Glacial.	Pliocene.

The foregoing table, though somewhat abridged, is fuller than it need be to show Willis's conception of the events which are of importance in the present connection. It will be observed that the relatively short period of time represented in the Pliocene and Pleistocene combined, is crowded with events to a degree seldom if ever matched in a modern geological study of a complex mountain system. No definite statement is given as to the strength of the initial relief which was brought low in the Methow peneplanation, but the implication from the paper is that the relief at the middle or later part of the Miocene was considerable. Further, we may believe that Willis shares the view stated by Smith in the companion paper of the same volume, which reads as follows:—

'The evidence of the reduction of a large area of folded Tertiary rocks to form the Cascade (Methow stage) lowland appears conclusive. The date of the development of this lowland is fairly well determined, since folds involving late Miocene strata are truncated, while on the other hand the subsequent history of a large part of the region has been so eventful that the production of the lowland surface could not reasonably have been later than Pliocene. Previous to this Pliocene reduction, erosion does not appear to have ever produced anything like a peneplain in the northern Cascades, as far as its history has been determined. In view of the eventful character of the whole of the Tertiary, it is plain that the period of reduction to base-level can not be considered as including any large part of Tertiary time, as has been suggested by Russell. Uplifts or subsidences of the extent that are known to have occurred during Eocene and Miocene time in this area must be considered as inaugurating new topographic cycles. Furthermore, the land surface that was flooded by the basalt flows at the beginning of the Miocene possessed considerable relief. This pre-Miocene topography has been preserved in a large measure from later erosion by the basalt, and where the capping is partially eroded away and stream canyons are cut down into the underlying formations the contact shows very conclusively the character of the old surface. Such a locality is the valley of Taneum creek, where it is at once seen that the prebasalt surface was such as to deserve to be termed rugged topography. It seems necessary, therefore, to restrict the period of the development of the Cascade lowland to the Pliocene.'*

Both Willis and Smith agree that the deformation of the Pliocene peneplain was not a simple uparching but a more complex uplift of the Cascade range through the association of local upwarps and downwarps. In the downwarps new river-courses were established, which are typified by those of the Methow, Wenatchee, upper Skagit, and the Pasayten rivers. These and other streams are thus supposed to be consequent on the late Pliocene warping of the peneplain developed in earlier Pliocene time. The lower course of the Skagit where it crosses the Skagit range, and the lower course of the Fraser where it

* G. O. Smith, Prof. Paper, No. 19, U.S. Geol., Survey, 1903, p. 28.

crosses the Coast range of British Columbia, are considered by Smith as antecedent to the late Pliocene uplift of the Cascade-Coast chain of mountains.*

The foregoing, rather liberal quotations from Russell, Willis, and Smith, show that these authors are in substantial agreement so far as the essentials of the later geological history of the Cascades are concerned, except that Russell refers much of the work of developing the Cascade peneplain lowland to the Miocene, while the other two authors consider that a truly mountainous topography characterized the region at the opening of the Pliocene. Besides its interest for the physiographer this skilfully presented hypothesis has great importance, if true, for the dynamic and historical geologist. This is not the place for its full discussion but the present writer is impelled to sketch the grounds for quite thorough-going disagreement with this hypothesis of the Cascade mountain system.

In the first place, the evidences for the existence of *any* general peneplain over the Cascades at any time in the history of the system seem extremely weak. Mere truncation of folds has no positive importance in the problem, for mountain-folds are effectually truncated when maturity is reached in a first erosion-cycle. The mere accordance of summit levels among the peaks is likewise to be expected at maturity of dissection in any range of alpine complexity, as will be shown in a succeeding section of this chapter.

Rather extended stream adjustment to soft rock-belts must be expected in a mountainous region which has reached maturity in a second cycle. This well known criterion is scarcely more than mentioned in any of the three papers quoted. The present writer believes, as a result of nearly three seasons' study in and near the Cascade field, that such evidence as there is on this point is against the idea of peneplanation in any part of Tertiary time.

Most stress is laid by Willis and Smith on the occurrence of flat-topped areas of relatively large size within the distinctly folded zone of the Miocene basalts.† There is no question that the anticlines of this district are truncated, but there is no question that it is dangerous to extrapolate on the curve of the profile in this small district out westward across the great Cascade range, in which similar *points d'appui* for this bold hypothesis of Pliocene peneplanation practically fail—fail according to Willis's own statement in the first of the foregoing quotations. There is no certainty that the local peneplain represented on the truncated arches of the basaltic territory was not formed far above sealevel or such a general baselevel as we must ascribe to the Cascade region during Pliocene peneplanation of the whole range. The recent studies of Passarge and Davis seem to prove the possibility of 'leveling without baseleveling' over large tracts of arid mountain-land. There is reason to think that the belt east of the present high Cascades may have been dry and subject to heavy wind-erosion for a comparatively long time. Under the control of the wind in an arid or subarid district newly uplifted rock-folds would suffer

* G. O. Smith and B. Willis, op. cit., and G. O. Smith, Bull. 235, U.S. Geol. Survey, 1904, p. 90.

† Prof. Paper No. 19, U.S. Geol. Survey, 1903, p. 26; cf. first quotation from Willis.

specially rapid attack.‡ Or, again, it is quite conceivable that a local Pliocene lowland of denudation was produced in this belt of weak folding under more normal climatic conditions. It is as easy to credit such an explanation for these few truncated, plateau-like folds in the basalt as it is difficult to credit a general peneplanation of the whole Cascade system and its later mature dissection—all within the limits of the Pliocene.

Willis and Smith both show that remnants of the Methow peneplain are extremely rare and always very small within the main Cascade range where they have examined it. They speak of 'broad crests' on a few summits which are taken to be residuals. The present writer believes that practically all of these can be explained as either in close organic relation to structural planes like the flat roofs of batholiths, or that they can be explained by the principle of the tree-line, as detailed in a following page. It may be noted that nearly all of Willis's profile sections which seem to give such a striking idea of a high-level plateau are drawn longitudinally through the ridges. Transverse sections would more clearly illustrate the generally deep dissection of the same region. The longitudinal profile does show sympathy with the profile of the canyon-cutting stream alongside the ridge; it cannot of itself prove two erosion-cycles. A set of transverse profiles would prove the general absence of high-level features which can with any certainty be classed as remnants of the old supposed peneplain. In other words, these latter profiles would not show 'topographic shoulders,' to use another of Davis's expressive terms to indicate the break in slope involved in any such two-cycle topographic systems as that here postulated by Willis, Smith, and Russell.

The most convincing argument against the hypothesis as stated by the two first mentioned authors, who ascribe the Methow peneplanation and the Entiat mature dissection entirely to the Pliocene, has already been given in principle in connection with Willis's hypothesis of a late Tertiary peneplanation of the Front ranges. If the extremely tough rocks of the Cascade range have been baselevelled since the Miocene, should we not expect the well determined Cretaceous peneplain of the Appalachian chain to have been destroyed since the early (or at least middle) Tertiary upwarping of that peneplain? Or should we not expect all local and even regional monadnocks like the sugar-loaf residuals of New England or like the White Mountains massif of New Hampshire to have been long since destroyed? No reason is apparent why the Cordilleran climate has ever favoured erosion in such colossal degree more than erosion has been favoured by the Appalachian climate. In many things the American West claims to be more speedy and powerful than the East, but such difference in the power of erosion as this cannot be conceded. And it is also true that the staple rocks of the Cascades are sensibly as resistant to the weather as those in the eastern highlands. It is true that in the states from Maryland to Alabama wide belts of the Appalachian chain have been peneplained in the Tertiary, but there the conditions were much more favourable to complete reduction than they were in the Cordillera at the close of the Laramide revolu-

‡ Cf. W. M. Davis, Journal of Geology, Vol. 13, 1905. p. 382.

tion. During the Eocene deformation of the Cretaceous peneplain in the southern Appalachians the uplift was, on the average, considerably less than 2,000 feet in the broader belts baselevelled in Tertiary time. We must believe that, in the Cordillera, the Laramide revolution developed very much higher land which was partly reduced during the Eocene, Oligocene, and early Miocene, yet was again increased by local uplifts at the close of the Miocene. Smith offers proofs that the topography at the close of the Miocene was strongly mountainous. It follows from the suggested hypothesis of two-cycle erosion in the Pliocene that this great relief of the Cordillera was, in the earlier part of that period, reduced to such flatness that later upwarps and downwarps could displace most of the rivers of the earlier cycle and force the development of a whole system of new streams flowing down the axes of the downwarps or draining the side slopes of those downwarps.

Hayes and Campbell point out a further special reason why the southern Appalachians were locally peneplained during the Tertiary.

> 'Although crystalline rocks are generally regarded as offering great resistance to erosion, they are, under baseleveling conditions, subject to very deep decay and probably at the close of the Cretaceous cycle were softened to a far greater depth than at the present time. As the elevation succeeding the Cretaceous period of baseleveling was not great, the streams quickly swept away this mantle of residual material down to baselevel. Under such conditions the Tertiary peneplain was very perfectly developed throughout the whole of the piedmont plain. The subsequent erosion of this peneplain has been comparatively slight and in many parts, especially in the vicinity of the James and Potomac rivers, it is almost perfectly preserved.'*

On account of the much greater amount of uplift in the Cascades we cannot credit a similar explanation for Tertiary baselevelling in that region.

Moreover, Hayes and Campbell have concluded that the principal upwarping of the Appalachian Cretaceous peneplain occurred at the beginning of the Eocene and that the baselevelling, so far as it went, was completed at the dawn of the Neocene. Similarly, Davis has dated the upwarp as 'early Tertiary.'† That is to say, in the Appalachians, as already sufficiently emphasized, all Neocene time has been engaged in the excavation of narrow valleys beneath the Tertiary peneplain. All post-Eocene time has been very far from sufficient to baselevel any large portion of the Appalachian uplift, initially low as it was after the mid-Tertiary upwarp.

In conclusion, therefore, we may hold that the Appalachian chain gives us a measure of all Tertiary time in terms of erosion, and that, by this standard, it seems impossible to accept the view of Smith and Willis as to Pliocene peneplanation followed by the later Pliocene mature dissection of the Cascade block.

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* C. W. Hayes and M. R. Campbell, National Geographic Magazine, Vol. 6, 1894, p. 86.

† W. M. Davis, Bull. Geol. Soc. America, Vol. 2, 1891, p. 578.

The present writer believes that the same conclusion must be drawn after an attentive comparison of the Cascade topography with that described in the Klamath mountains of Oregon and northern California. Diller describes a peneplain there locally developed on the relatively weak rocks of the upturned Shasta-Chico series in the immediate vicinity of the sea or of the Sacramento river which has long been near sealevel. It is possible, as Diller holds, that this proved peneplain once extended over the harder rocks of the range as well as over the Sierra Nevada, although Lindgren shows that the Sierra was not a peneplain at the opening of the Auriferous Gravel period. We may quote Diller's summary:—

> 'The erosion necessary to develop the baselevel [peneplain in the sense meant in the present report] out of the topography resulting from the uplift at the close of the Shasta-Chico period must have occupied a long interval of time, possibly beginning in the later part of the Cretaceous and continuing through the Eocene and earlier portion of the Miocene, but as the plain appears to have attained its maximum extent during the Miocene, it may be referred to as the Miocene baselevel.'*

Thus, in a Cordilleran region which probably underwent erosion at about as fast a rate as that characterizing Tertiary erosion at the Forty-ninth Parallel, we have a Miocene peneplain still preserved on rocks (Cretaceous) which are much weaker than the staple rocks of the Cascades. All the more readily can we exclude the possibility of a well perfected Pliocene peneplain in the northern range.

The foregoing argument applies also, with nearly all its force, against the hypothesis of Russell that the Cascades were peneplained in post-Eocene time from a condition of strong, mountainous relief in the late Eocene period. It does not seem necessary to restate the argument for this case.

As an alternative hypothesis, therefore, the present writer offers the view that all post-Laramie time has been occupied in the production of mature mountain topography in the Cascades. The initial stage is taken to be that of the new relief left as a result of the Laramide orogenic revolution. Local, often severe deformations have, at a few intervals since (especially in the late Miocene), complicated the history of the range which was hoisted up in that revolution. There is, further, good reason to think that near the beginning of the Pliocene there was some, rather general uplift of the system, still further adding to the task of producing the deep canyons and wider valleys of these mountains. Such crustal movements have formed episodes in a single period of erosion in a district which has always been mountainous since the Laramide revolution. Before the later, probably Pliocene, massive uplift to which many of the deep, narrow canyons are due, the relief may have approximated late maturity of form or locally even old age—a mountain-torso landscape—but true peneplanation on a large scale within Tertiary time is expressly excluded by this alternative hypothesis. Large-scale peneplanation of large parts of the

* J. S. Diller, 14th Ann. Rep. U.S. Geol. Survey, Part 2, 1894, p. 420.

Cordillera may have been completed during the Cretaceous, when the enormously thick Shasta-Chico beds were accumulated. The writer does, then, favour the peneplain theory as applied for other times and places; but he fears that the hypothesis of late Tertiary or mid-Tertiary peneplanation in the Cascades may obscure the essential facts of their post-Laramie geology.

Before discussing this favoured conception of the Cascades further, it is well to review the correlative explanation of the accordance of summit levels in high mountains. This is an important phase of the argument for one erosion cycle and against two cycles in the Tertiary history of the Cascades, as, indeed, for practically all of the trans-Cordilleran section at the Forty-ninth Parallel.

Development of Accordance of Summit Levels in Alpine Mountains.

In 1905 the writer published a paper on this subject with intent to emphasize a 'composite' explanation of summit-level accordance as the normal product of the forces which act on a complex mountain range up to the mature stage of its first erosion cycle.* This explanation is opposed to that in terms of two erosion-cycles involving the uplift of a peneplain. In the years which have followed, the writer's additional field and laboratory studies have tended to confirm belief in the 'composite,' one-cycle hypothesis. A digest of the preliminary paper will here be given, together with some further illustration of important points, taken from the region covered by the Forty-ninth Parallel survey.

In the present section the term 'alpine range' is used to signify a range possessing not only the rugged, peak-and-sierra form of the Swiss Alps, but, as well, the internal structures incidental to intense crumpling, metamorphism, and igneous intrusion as exemplified in the Swiss Alps.

The word 'accordance' is used advisedly. 'Equality' of heights is not meant by those observers who have given the question the best attention. For limited areas 'subequality' of the summits is a fact, but over wider stretches, and especially over the whole of a single range, even subequality fails, and the accordance takes the form of sympathy among the peaks whose tops in companies or in battalions rise or fall together in imaginary surfaces often far removed from the spheroidal curve of the earth. In general, the imaginary surface which will include the higher summits of peaks and ridges in an alpine range has the form of a low arch, highest in the interior of the range and elongated in the direction of the main structural axis of the range. Subordinate, but usual and systematic, complications in the form of this imaginary surface are found in transverse crenulations which alternately depress and raise the surface from its average out-sloping position on the margin of the great arch. The axes of these transverse depressions are often suspiciously coincident with existing drainage courses.

There is, then, at least one orderly element in the 'chaos' or 'tumbling sea' of mountains visible from a dominating point in any one of a goodly

* R. A. Daly, Journal of Geology, Vol. 13, 1905, pp. 105-125.

number of alpine ranges. The accordance of summit altitudes has been noted in the Alps, in parts of the Caucasus, in the Pyrenees, in the Sierra Nevada of California, in the Alaskan ranges, in the Canadian Selkirks and Coast range, and in the American Cascade range. We have seen that Willis regards the accordance of summit levels in the Galton-MacDonald mountain system as an indication of an uplifted mid-Tertiary peneplain. An illustration of the phenomenon is given in Plates 52, 66, 68, and 73 C. Views in other ranges traversed by the Boundary belt are given in Plates 26, 28, and 45.

The fact of accordance is established, while the theories of explanation are very various. That they need critical examination and sifting is clear, not only for the sake of the important fact of accordance itself, but also for the reason that these theories involve widely diverging views on great physiographic revolutions. Geological history in long chapters is thereby as expressly implied as it would be by the interpretation of purely stratigraphic evidences, illustrating over and over again the truth that both classes of evidences are required in building up a complete history of the earth. Not only do these theories involve premises regarding great denudations, but, as well, a multitude of details concerning river history and the evolution of individual mountain massifs. There are likewise involved correlative views of the physiographic development of the neighbouring regions, both on the large scale and in details. Geographic description and nomenclature should be controlled by reference to the correct theory or theories of land-form origins. Finally, large conclusions concerning the origin of the force of mountain uplift must follow in the wake of certain of the hypotheses already announced to explain the phenomenon of accordance in summit levels. The attempt has even been made to connect the origin of fractures and of mineral veins with the specialized kind of crustal movement imagined for one explanation of this accordance.* There are thus abundant reasons for coming to a wise decision as to the best explanation of the fact.

The hypotheses dealing with this sympathetic attitude of alpine summits may be classified on the basis of the logical explanation of an organism. (*a*) How far is the feature in question due to *inheritance?* (*b*) How far is it due to *spontaneous development* in the present environment? A review of the hypotheses shows, everywhere and naturally, emphasis placed on erosion, but the writer believes that the possibilities of inheritance are only partially worked out, and, again, that the methods of spontaneous development are not yet brought into the proper balance for final discussion or decision on the question.

I. EXPLANATIONS BY INHERITANCE.

1. Among the various explanations by inheritance we have, first, the *peneplain* theory, which need not further be discussed in this place.

2. *Hypothesis of original rough accordance of summit levels, due to isostatic adjustment.*—Basal to all of the alternative hypotheses is the inquiry as to

* A. C. Spencer. Transactions of the Amer. Institute of Mining Engineers, Oct., 1904, p. 35.

Accordant summit levels in the Selkirk range. Photograph taken from southern end of Beaver Mountain ridge, six thousand feet above sea. Looking southeast.

the original form of the range at the geological moment when paroxysmal folding of its rocks was practically completed. It is self-evident that the term 'original' is here used arbitrarily, but the strain on language may be permitted in thus conveniently naming and emphasizing a principal epoch in the early history of the range.

At first sight one may be surprised to find this accordance of summit levels among high mountains of complex structure. Surprise should be tempered, however, by the consideration that the original relief was not even approximately determined by constructional profiles deducible from existing structures.

It is, for example, highly improbable that the 'reconstruction' of a great alpine anticline through a study of its denuded roots can represent the original height of its crest above sea-level. Nor is it legitimate to conclude from the great shortening of the transverse axis of the range by the enormous tangential pressures that orogenic blocks of indefinite height could have been produced. Overthrusting, upthrusting, folding, mashing, and igneous intrusion have often occurred on such a scale, that were it not for other and inhibiting causes, differential elevations perhaps forty or fifty thousand or more feet in relative height might have resulted. No geologist believes that local blocks of such height have entered into the construction of any terrestrial range. Erosion during the absolutely slow, though relatively rapid, growth of the range has often been appealed to as sufficient to explain the lack of such heights in even the youngest alps of the world. But not sufficient emphasis has been placed on the quite different control of isostatic adjustment accompanying and following the paroxysmal uplift of orogenic blocks. Single steep slopes of possibly thirty thousand feet might, indeed, then exist if they were underlain by the strongest granite, which likewise formed the underpinning of the whole adjoining district, that granite being throughout at the temperatures of ordinary rock-crushing experiments. But such towering masses are highly improbable for weaker rocks which would crush down under the supposed conditions, and wholly impossible for mountain blocks overlying material as plastic as that which composes the original basement of an alpine range. The strength of the main mass of the range is diminished by the inevitable rise of subsurface temperatures with crumpling and mashing. It is the rule with alpine ranges that intrusions of hot magma on a huge scale either accompany or very soon follow the chief paroxysms of folding. In either case, and not only over the areas where denudation has exposed the intrusives, but also over much wider areas about the downwardly expanding bases of the batholiths, the heat of the intrusions still further increases the plasticity of the basement on which the mountains are growing. The weakness of the underpinning is further manifest in the case of such ranges as the Cascades or the Coast range of British Columbia, so largely formed of granitic magma injected in a fluid state during or just after the last great period of plication in those ranges.

The conclusion seems unavoidable that the tendency of tangential force to erect orogenic blocks projecting much higher into the air than Mount Everest itself is operative only up to a certain critical point. Beyond that point the increasing weight of the growing block and the increasing plasticity of its basement call in another kind of movement due to the gravitative downcrushing of the block. As a whole, or in fragments separated from each other by normal faults, the block will assume a shape and position suitable to static equilibrium for the whole range. The range might conceivably find that equilibrium when the entire uplift has attained the form of an elongated arch accidented by already roughly accordant mountain summits. At any rate, subequality of height might characterize large areas.

This whole phase of gravitative adjustment forms a problem clearly indeterminate in the present state of geological physics. Critical laboratory experiments have yet to be devised, and careful, special field-work devoted to the problem, before it can attain even an approximate solution. So far as it goes, however, gravitative adjustment of the kind just described aids all the other processes tending toward summit-level accordance.

In this connection we may note the prevalence of normal faults in the Purcell mountain system, which is one of the most noteworthy of all the ranges in showing summit-level accordance on a large scale. As stated in the chapter on the stratigraphy and structure of the Purcells, most of these faults have probably been developed as a result of crustal adjustments following the severe upturning of the Laramide revolution.

3. *Hypothesis of original rough accordance, due to differential erosion during the period of alpine plication.*—Co-operating with isostatic adjustment is the effect of the special erosive attack on each rising block from the moment it once begins to dominate its surroundings. On the average, the forces of weather and waste are most destructive on the summits of this time, as they shall be through all the subsequent history of the range as an alpine relief. Denudation is in some direct ratio to the height of uplift. Higher summits are thereby reduced, while lower ones are still growing under the stress of mountain-building. How far erosion thus checks the upward growth of the rising massifs probably cannot be measured, but such differential destruction must develop still further the rough summit-level accordance already in part established by isostatic adjustment.

The downcrushing of higher, heavier blocks with the simultaneous rise of their lower, lighter neighbours, coupled with the likewise simultaneous, specially rapid loss of substance on the higher summits, form a compound process leading toward a single, relatively simple result. In both the architecture and the sculpture of her alpine temple, Nature decrees that its new domes and minarets shall not be indefinitely varied in height. Such accordance as they have among themselves will be preserved and accentuated as her chisels fashion new details on the building. The accordance of the present time in any alpine range is in part inherited from what, in this paper, has been called the 'original' form of the range. The original form meant a first approximation to the result; the later, spontaneous modification of that form means a second approximation to perfect accordance.

In passing to an analysis of erosion events following the epoch of folding, we are, therefore, illustrating the cumulative force of both the hypotheses so far

Plateau-like surface of Remmel batholith. Looking southwest from Commission trail four miles west of Cathedral Peak, Okanagan Range. The shallow valley in foreground is underlain by the long belt of Ashnola gabbro and is probably of subsequent origin.

Plateau-like surface of unroofed Similkameen batholith ; looking southwest from base of Mount Chopaka, Okanagan Range.

discussed as alternative with, and as against, the peneplain hypothesis for truly alpine ranges. By the peneplain hypothesis, the accordance of summit-levels was most perfect in the initial stage of the physiographic cycle begun by the upwarping of the peneplain; by that hypothesis mature dissection of the range tends to destroy something of the initial accordance. The alternative, composite explanation, already in part outlined, involves the conclusion that the accordance tends to become more and more perfect as the stage of mature dissection of the newly folded range is reached. The question remains whether the accordance inherited from the forms original from the epoch of plication may be so much further developed by subsequent erosion in the physiographic cycle initiated by that plication, as to give the amount of accordance actually observed in the existing range.

II. SPONTANEOUS DEVELOPMENT OF SUMMIT-LEVEL ACCORDANCE.

1. *Spontaneous development by isostatic adjustment.*—The last paroxysm of crumple and upthrust in the young alpine range has occurred. Henceforth its forms are to be determined chiefly by erosive processes—yet not altogether so. Several authors have suggested that the levelling influence of gravity is not only manifest in the piecemeal carriage of rock fragments out to the piedmonts, or finally to the sea; but that also the very accordance of summit levels is in large part related to gravitative adjustment on a large scale. Where, for any cause or causes, denudation significantly lowers a localized area of the range faster than neighbouring areas of the same altitude, the former area will tend to rise, the surrounding region to sink, so as to reproduce conditions of equilibrium in the range. This view entails belief once again in the principle of isostasy. The appeal to the principle in the present case is all the more worthy because of the long continuance of the special plasticity belonging to the very slowly cooling basement of a recently folded alpine range.

2. *Metamorphism and igneous intrusion in relation to the degradation of mountains.*—It is a truism that the rocks of any alpine range vary enormously in composition and structure. It is quite as true that their resistance to weathering and wasting is far less variable.

Secondly, the original upper surface of the zone of intense metamorphism is almost certainly much less uneven than the outer surface of the original range.

Thirdly, many of the great intrusive bodies of alpine ranges had originally themselves a demonstrably dome-like form with broad, flattish tops. If the writer is correct in holding that the patches of Anarchist schists and other of the older rocks occurring within the area of the Similkameen batholith are true roof-pendants, it seems probable that the present erosion surface on this large mass is not far from the position of the original roof of the batholith. The reader will recall similar cases described or mapped in the Sierra Nevada and elsewhere.

The foregoing statement of a difficult theme is brief, but it suffices to suggest the bearing of metamorphism and intrusion on the question of accordance. In what has been defined as its original state, an alpine range was composed of a hard, comparatively homogeneous core covered with a relatively thin veneer of already somewhat eroded, unmetamorphosed rock. The core is to be conceived as having an upper, limiting surface, with the form of a long, flat arch bearing subsidiary, low, broad, boss-like arches and domes. The erosion of the unmetamorphosed cover will go on apace. The erosion of the core, the main mass of the range, will progress much more slowly. Erosion may thus sweep away wide areas of the cover before the individual mountains between canyons sunk in the core have suffered significant loss of height by denudation. In such areas accordance of summit levels would henceforth be expected because of the original flattish tops of the core, and because of the comparative homogeneity of the core-rocks. For the same reasons, accordance among the summits of mountains cut out of a granite batholith would be expected. Where, however, the granite is distinctly harder than the surrounding metamorphics, there would not be simultaneous accordance with the summit levels of the metamorphic mountains, except for causes other than the two just described. As the composite explanation of accordance is further outlined, it will be seen that such other causes may operate effectively in some cases. Yet the common, special dominance of granite peaks in a truly alpine range agrees as well with the composite explanation as it does with their reference to the class of monadnocks on the peneplain theory.

3. *The influence of local glaciation on summit altitudes.*—Hitherto no detailed distinction has been necessary among the varied phases of erosion. It may now be noted that the work of high-level glaciers, if long continued, tends on the whole to produce summit-level accordance. In each glacier there are two loci of maximum erosion; one at the head of the glacier where the great bergschrund separates the ice from the solid rock of the head-wall; the other beneath the central zone of the glacier itself some distance upstream from the foot of the glacier. One result, noteworthy in the present connection, is to drive the headwall of the growing cirque farther and farther into the mountain. In the nature of the case, it will be the higher peaks which are most vigorously attacked. From every side, it may be, comes the attack on the massif which, for any cause, specially projects above the general level of the range. Owing to the rapidity of the ice-erosion, that summit must tend to fall and reach something like accordance with its formerly lower, unglaciated or but lightly glaciated neighbours.

We have seen that all across the Cordillera the highest peaks and ridges long suffered specially powerful attack, as they alone stood high enough to wear the fatal belts of bergschrund. During the ice period, they were nunataks and lost substance like nunataks; the loftiest peaks losing most, the lower ones with less linear extent of bergschrund, losing proportionately less. Peaks and ridges not penetrating the general surface of the Cordilleran glacier lost nothing by special schrund-line attack.*

* Compare the views of W. D. Johnson and G. K. Gilbert, as announced in the *Journal of Geology*, Dec., 1904. The special glacial attack on the highest summit of the Big Horn Range (Cloud Peak) is excellently illustrated in the well-known paper by Matthes, *Twenty-first Annual Report*, U.S. Geol. Survey, Part II, 1899-1900, Plate XXIII.

It is certain that this differential erosion was long continued during the Pleistocene period in each of the ranges where accordance of summit levels has been discussed. Pleistocene glaciation certainly tended to bring the high Front ranges of the Rockies into accordance with the lower Galton and Purcell ranges. There is every reason to suppose that like conditions and like results would characterize still earlier glaciations.

In summary, then, it may be said that partial explanation for summit-level accordance is to be sought in a special, characteristic control of alpine climates. In general, the climate of high levels is a glacial climate. In general, glacial erosion is very great and the bulk of it is high-level erosion. In general, local glaciers and glacial erosion are most abundant and long-lived about the highest summits. One net result of glaciation is to cause the specially rapid wastage of those summits and to produce rough accordance among the peaks.

4. *The influence of the forest cap on summit altitudes.*—Climate not only breeds glaciers in the high levels of an alpine range; it normally determines a more or less well-defined tree-line. The treeless zone is always more extensive in area than the glacier-bearing zone, but the upper limit of trees is often not far from coincident with the lower limit of the zone of cirque glaciers. It is logical to find here a place for the theory that widespread accordance of summit levels in an alpine range is related to the differential rate of erosion above and below tree-line. The theory is so well known that it needs no special detailed statement on the present occasion. Let it suffice to recall the principal reasons why denudation is faster above tree-line than below, and once more note the inevitable conclusion from that fact.

a. *Disintegration of rock.*—Both as an evidence of incomparably more rapid frost attack above tree-line than below, and as a condition for more effective attack by agents other than frost, the 'Felsenmeer' is significant. Illustrations of this rock-chaos so characteristic of hundreds of peaks in the Boundary belt are shown in Plates 32, 42 B, 70, and 71 B.

b. *Removal of rock-waste.*—On the other hand, the streaming of weathered material down the slopes is, other things being equal, probably several times more rapid in the treeless zone than below it.

(1) The direct beat and *wash of the rain* have practically negligible effect on waste-removal below tree-line. The power of heavy rain washing the treeless zone, either in the derived form of rills or as a sheet flood, is manifest to anyone who has experienced a good shower above tree-line.

(2) During the Boundary survey the writer has for the first time become conscious of the importance of *burrowing mammals* in preparing loose rock-waste for speedy transit to the valleys. In the western Cordillera field-mice, gophers, moles, marmots, bears, and other species are each year doing an immense geological work. There can be no exaggeration in saying that these burrowers annually turn over hundreds of thousands, if not millions, of tons of soil or disintegrated rock in either the Coast range or the Selkirk range of British Columbia. Such work is of relatively little importance where mounds or fillings of snow tunnels are protected by trees overhead. It is very different above tree-line, where even

the weak veneer of turf is broken in the burrowing, and where the millions of mounds or tunnel-casts are exposed to every agent of transportation.

(3) The transporting efficiency of *wind* in the treeless zone of lofty mountains has, on the whole, been more emphasized by European observers than by those of America. So far as this is the case, Europeans have come nearer to the highland view than we have in this country. The summer quiet of alpine summits of itself gives a most deceptive idea of the power of wind in the heights. During the other seasons winds of almost hurricane violence are far from uncommon, if we can generalize from the limited instrumental data so far issued from high-lying observatories. We may believe that dust, sand, and fine gravels are so rare above tree-line largely because of such winds. For obvious reasons, sand-blasting there plays no such rôle as it does in the sculpturing of rock-forms in lowland deserts; but transportation by the wind is another influence placing in strong contrast the conditions of erosion in the regions above and below tree-line.

(4) Erosion and transport through *avalanches* are enacted in both the treeless and the forested zone. In the lower zone the destruction wrought by a great avalanche may be great, but it is largely a ruin of tree-trunks. In the lower zone the avalanche paths are tolerably well fixed from year to year, sparing much the greatest part of the forested area. In the treeless zone, avalanches have generally less momentum, but they are more numerous, less localized, and therefore more likely to find and sweep down loose rock débris. Above tree-line their ruin is wholly rock-ruin. It seems safe to conclude that snow-slides are more powerful agents of degradation above tree-line than below.

(5) The general streaming and cascading of rock-waste under the direct pull of *gravity* are evidently immensely more rapid in the treeless zone than where the strong vegetation mat binds humus, soil and boulder to the bed-rock, though it be without perfect, ultimate success. The fine-grained felsenmeers of the more friable peaks in the Boundary belt were often found to be mobile under very slight pressure, such as that of a man's foot. Many of the summits are ornamented with terracelets of loose débris which tends to stream down the slope but is held in front by bands of turf. Many of these small tongues of rock-waste are moving on slopes as low as one or two degrees. Similar forms in great abundance may be seen in the treeless parts of Labrador and Alaska, and again often on relatively flat slopes. Hundreds of the scallops, each covering a few to many square yards may be counted on a single summit in the Front ranges or in the Okanagan range—in all cases above tree-line. After six seasons of work on the Boundary belt the writer feels convinced that the mere streaming of waste in the treeless levels of the Cordillera is competent to produce tolerably wide and flat crests on the mountain ridges, though it is not clear that the wind is not even more competent. Perhaps the finest illustrations of the combined effects of these two agencies are to be seen on the granite summits of the Okanagan range, where miniature plateaus have often been developed above tree-line. The writer suspects that the influence of the tree-line has, in fact, been responsible for some of the 'peneplain remnants' mapped by Willis and Smith.

Meadow and park near tree-line, about six thousand feet above sea level, Bonnington Range.

Coarse felsenmeer in massive grit of the Wolf formation; summit of the Selkirk range, north of Dewdney trail; about seven thousand feet above sea.

Coarse felsenmeer in quartzite of the Ripple formation; southeastern slope of Mt. Ripple, Selkirk range; seven thousand feet above sea.

Looking south along ridge between Middle and Slesse creeks, Skagit Range. View illustrates glacial and frost attack on ledges above tree-line.

Southern slope of Mount Ripple, Selkirk Range, showing one of the most extensive felsenmeers in the Boundary belt. The absence of continuous forest-cap permits rapid streaming of rock-waste.

(6) The débris from the treeless zone naturally helps to protect the bed-rock of the forested zone; the faster the wasting above, the slower is the bed-rock destruction below. This exceedingly important argument needs no expansion.

(7) The *chemical solution* of rock is, to be sure, probably more rapid beneath the forest-cap than it is above tree-line where the amount of vegetable acid is at a minimum. This cause may, however, be believed to do little toward counterbalancing the effect of the combined causes just enumerated. Erosion in alpine mountains takes place primarily by the removal of masses; in comparison, molecular transfer of rock material to the low grounds has but a very minor control.

Conclusion.—A review of the conditions of general degradation shows clearly its differential character above and below tree-line. Summits already reduced to the tree-line are bound henceforth to be stubborn against further erosion. Summits bearing a treeless zone are as clearly bound to continue wasting rapidly so as to tend to approach accordance of summit levels with their tree-covered neighbours. Since the glaciated zone of alpine mountains is, in general, well within the treeless zone, the special degradation due to local glaciers harmonizes with general erosion in the development of accordance.

The different mountain ranges of the Forty-ninth Parallel section all show summit-level accordance and, in each case, at an elevation closely similar to that of the effective tree-line. The following table shows the observed position of this line in the higher ranges.

—	Average range in position of tree-line. Elevations in feet above sea level.	Average elevation of tree-line, below which forest effective in retarding erosion: approximate measure in feet.
Clarke range	7,500-7,200	7,200
Galton range	7,500-7,300	7,200
Purcell range	7,100-6,800	7,000
Selkirk range	7,100-6,800	7,000
Columbia system	7,000-6,000	6,500
Okanagan range	7,200-6,500	6,600
Hozomeen range	7,500-6,500	7,000
Skagit range	6,800-5,800	6,000

In all cases the 'turf-line' is higher, occasionally rising to 1,000 feet or more above the effective tree-line. An inspection of the maps shows the sympathy between effective tree-line and summit-level accordance, and powerfully suggests that Dawson was right in explaining it as largely due to the tree-line's influence.

On the other hand, Willis opposes Dawson's explanation with the following argument:—

'The activities of erosion do not appear to tend toward more uniform effects with greater altitude, on the contrary elevation emphasizes their locally unequal intensities. Corrasion and transportation are effected by falling water, whose energy for a given mass is directly as the fall, and consequently increases with height of land. Corrasion and transportation are very narrowly localized in activity, and hold the same relation to general degradation that a circular saw does to a planer. Their intense application results in deep canyons, the extreme of height and depth. Disintegrating influences, whether chemical or mechanical, may act equally with equal opportunity, but they are controlled by conditions of exposure. Upon an uneven surface these are varied and they become more and more diverse as inequalities of relief develop. The suggestion that frost and thaw may with elevation gain in effectiveness more rapidly than corrasion and so may limit the height to which peaks may attain in a growing range, appears not to be sustained by study of mountains much higher than the Cascades, nor by theoretical reasoning in regard to the work of freezing water. Thus after careful consideration the writer has felt obliged to abandon the hypothesis of development of a common high level among mountain peaks.'*

The reply to this argument is implied in much that has preceded in the present chapter. A chief objection to it consists in the fact that under the arid conditions above tree-line we have in falling water only one, and perhaps not the most important, cause of erosion. Waste-streaming, wind-action, snow-creep, and avalanches must also be considered. It seems clear, therefore, that Willis's argument is inconclusive; it does not support the two-cycle hypothesis of the Cascade range topography.

Accordance Through River-spacing and Gradation of Slopes.—A fifth method for the spontaneous development of summit-level accordance remains to be noted. The recent announcement and discussion of this explanation make it superfluous to present here more than the briefest of the underlying ideas.†

Professor Shaler in America and Professor Richter in Europe have independently shown that, as mature dissection of a region under normal climatic conditions is reached, rivers of the same class tend to become nearly equally spaced. In perfect maturity the slopes of the interstream ridges are graded from top to bottom. This gradation of the slopes draining into two adjacent, nearly parallel streams flowing in the same direction, produces a comparatively even longitudinal profile of the intervening ridge. The even crest of the ridge must be more or less sympathetic with the profiles of the streams below, and,

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* B. Willis, Prof. Paper No. 19, U.S. Geol. Survey, 1903, p. 74.

† Cf. R. S. Tarr, American Geologist, Vol. 21, 1898, p. 351; N.S. Shaler, Bull. Geol. Soc. America, Vol. 10, 1899, p. 263; W. S. T. Smith, Bull. Department Geology, University of California, Vol. 2, 1899, p. 155; E. Richter, Zeitschrift des deutschen und österreichischen Alpenvereins, Vol. 30, 1899, p. 18; W. M. Davis, American Geologist, Vol. 23, 1899, p. 207.

down stream, slowly attain a lower and lower level. Local notches or cols may be gnawed in the ridge, but all the summits must be roughly accordant, though, of course, not uniform, in altitude. Other things being equal, the more mature the dissection, the more perfect the summit-level accordance; but the principle may be applied to alpine ranges. In those ranges the actual imperfect degree of accordance may often match the imperfectly matured state of dissection.

SUMMARY.

The form of the preceding discussion has been analytical, but its main point has been to emphasize the synthetic nature of the process of mountain sculpture. Seven different conditions of erosion *work together* to produce accordance of summit levels in an ideal alpine range undergoing its first cycle of physiographic development. Isostatic adjustment and simultaneous, differential degradation of rising blocks tend to bring about rough accordance of summit levels in the range as 'originally' formed. Later differential erosion and consequent further isostatic adjustment, the influence of metamorphism and intrusion, the sculpture due to high-level glaciation, the normal existence of a high-level tree-line, and, finally, the compound process of river spacing and slope gradation —all these may combine their effects and render more perfect the accordance of levels inherited from the early, growing period of the range.

This composite explanation must, therefore, be considered very carefully in discussing the origin of the present relief in an alpine range where there are no remnant plateaus directly referable to a common, uplifted and dissected peneplain. Such accordance may give a comparatively even sky-line in views from any dominating point, but the full force of the composite explanation is directed against the reference of that even sky-line to the direct or inherited profile of a peneplained surface.

General Conclusions on the Physiographic History of the Cordillera at the Forty-ninth Parallel.

Mild deformation of Eocene, Oligocene, and Miocene formations in contrast with strong deformation of Upper Cretaceous and older formations at many points in the middle and northern parts of the Cordillera represents a combination of facts which clearly date the last general orogenic revolution at the close of the Cretaceous period. The findings at the Forty-ninth Parallel in this matter corroborate the conclusion of Dawson, McConnell, Dana, and others who have devoted special attention to these mountains.

The topography resulting from the Laramide revolution was one of great relief and of most intricate design.

The dominance of quartzites, hard schists, massive limestones and dolomites, and granites in the Forty-ninth Parallel section explain the obvious fact that the Cordillera is here a gigantic highland unit which is specially stubborn against attack by erosive agencies.

The work of reducing the original chain of early-Eocene mountains to the present more subdued relief is of the same order as that accomplished by the erosion which was active through the entire Tertiary period in the equally resistant terranes of the Appalachians and of other mountain-chains. The opening of Waterton lake valley, the Rocky Mountain and Purcell trenches, the Selkirk Valley, and the Okanagan valley forms a series of tasks comparable to those of opening the Great Valley, or the Hudson, Connecticut, or Berkshire valleys of the east. The many narrower valleys of the Cordillera are analogues of the young to mature Tertiary valleys cut in the Cretaceous peneplain of the Appalachians.

Some individual canyons of the Cordillera are due to rearrangements of drainage through glacial action or through river-capture, or through other exceptional causes; but there is little doubt that there has been a general uplift of the Cordillera in this latitude during the late Tertiary. The relief has consequently been increased—perhaps by as much as that claimed by Dawson, 2,000 feet, for the Belt of Interior Plateaus.* Such uplift is an important incident complicating but not radically changing the erosion conditions which already existed before the elevation. Before it took place, we may believe that the mountains all the way from the Gulf of Georgia to the Great Plains, ranged in height from 3,000 to 8,000 feet or more. This late Tertiary uplift invigorated the rivers; it did not begin a new erosion cycle at the close of a completed former cycle.

The view that the entire post-Laramie history belongs to one complex erosion-cycle explains the apparent predominance of consequent drainage in all the ranges here constituting the Cordillera. It also tends to explain the absence of well-defined adjusted drainage which is so noticeable in the trans-Cordilleran belt. Of course, we should not expect even a second erosion cycle to produce in this mountain-chain the extraordinary amount of subsequent drainage which characterizes the very heterogeneous terranes of Virginia and Pennsylvania. The local Cordilleran rocks are too nearly uniform in ‘ hardness ’ for that.

This outlined history has the advantage of not overloading the Tertiary with what seem to be impossible feats of erosion. The vast denudation proved in the soft rocks of the High Plateaus of the United States is a quite different phenomenon from that postulated by the advocates of Tertiary peneplanation in the exceedingly strong rocks of the ranges crossed by the Forty-ninth Parallel. The Tertiary period was long; the question is, how long? The attentive study of erosion will help in answering that question, but there must be a lithological control over speculation and, above all, a careful comparison of records from all parts of the world. The hypothesis of late Tertiary peneplanation at the Forty-ninth Parallel section of the Cordillera cannot be reconciled with the facts showing the speed of erosion in eastern America or in Europe, nor with the physiographic histories which seem so firmly established in those large areas of the earth's surface.

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* G. M. Dawson, Bull. Geol. Soc. America, Vol. 12, 1901, p. 90.

CHAPTER XXIII.

FIRST CALCAREOUS FOSSILS AND THE ORIGIN OF THE PRE-SILURIAN LIMESTONES.

Introductory—Abstract of Chapter.

The writer has spent most of each of three field seasons in the study of the Cambrian-Belt geosynclinal and, as abundantly indicated in the previous chapters, failed to find calcareous fossils at any point, unless the doubtful forms referred to Cryptozoon be of truly organic origin. Essentially the same experience was met with by Peale, Weed, Pirsson, Walcott, Weller, Willis, Ransome, Calkins, MacDonald, Lindgren, Dawson, McEvoy and others who have worked on these old rocks. Where so many geologists and expert paleontologists have not succeeded in this principal quest, it is clear that fossils of any kind are generally very much rarer than are those of younger Paleozoic formations in the Cordillera.

The cause of the failure of calcareous fossils is one of the leading paleontological and geophysical problems in connection with the prism. The explanation cannot be found in the supposition that the fossils were once present and have been removed or have become unrecognizable through the metamorphism of the strata. The static metamorphism actually undergone has not been of the kind or degree which would involve the wholesale destruction of shells or skeletons. On the other hand the rocks are strikingly free from evidences of dynamic metamorphism except in certain limited areas of the Boundary belt. The rock-exposures are generally large and favourable to the discovery of fossils if they were really enclosed in the rocks. The organic remains found in the Greyson, Altyn, Castle Mountain, and Bow River formations, are almost entirely tests or fragments of crustaceans, in which the material is largely chitin. Whatever discoveries there may be in the future, it is certain that calcareous animal remains are exceedingly rare in the Cambrian and Beltian rocks of the whole Forty-ninth Parallel section. They are likewise very rare or quite absent in the thick sedimentary mass of the Priest River terrane, in which the writer was able to find not a single trace of organisms.

This unfossiliferous character of the different terranes is all the more noteworthy because of the immense thicknesses of limestones represented. The obvious fact that the limestones have not the characters of deposits due to the accumulation of shells or to coral growth and thus to processes generally credited with the formation of marine limestones, offers a second problem closely related to the first. The writer has offered a hypothetical explanation of (1) the lack of calcareous fossils in these Forty-ninth Parallel formations, and (2) the general failure of fossils in the pre-Cambrian and most Cambrian formations throughout the world. The hypothesis also accounts for the development of the dolomites and limestones of pre-Silurian age. The explanation is necessarily to some extent founded on speculation. The difficulty and importance of the problems demand that even such speculative explanations should be retained and elaborated before the final theory is adopted. For this reason the present chapter contains a statement of the hypothesis in some detail.

The secretion of calcareous hard parts by marine organisms is supposed to have been first made possible as a result of the increase of the land areas during the late-Huronian orogenic revolution. (See two preliminary papers.)* That enlargement of the continents caused a great increase in the annual supply of river-borne salts to the ocean. The supply was specially increased by the upturning and erosion of the thick limestones which had been deposited on the sea floor of earlier pre-Cambrian time. These limestones are regarded, on the hypothesis, as precipitates of calcium and magnesian carbonates, thrown down when the river-borne salts diffused to the ancient sea bottom. The chief reagent for the precipitation is considered to be the ammonium carbonate generated by the decay of animal matter. It is further postulated that in pre-Cambrian time the active scavenging system had not yet been evolved; that therefore the amount of decaying animal matter on the pre-Cambrian sea floor was vastly greater than the amount now allowed to decay on the bottom of the ocean. The smallness of the annual supply of river-borne calcium salts, coupled with this specially rapid precipitation of calcium carbonate, is supposed to have kept the pre-Huronian ocean nearly limeless; only the minute traces of calcium salts contained in the river waters as they diffused to the sea bottom would be found in the ocean of that time. At the bottom the water would be practically limeless.

The nearly limeless condition of the surface water was changed by the extensive orogenic and epeirogenic movements of late-Huronian time. In the Cambrian period the animal species had begun to armour themselves with the new material, henceforth present in the sea-water in sufficient amount. The primitive chitinous shell now became strengthened with phosphate and carbonate of calcium, and in the Ordovician many species had adopted the armour or skeleton of pure calcium carbonate. The Ordovician and Silurian rocks were therefore the first to be charged with calcium carbonate shells and skeletons in great numbers.

The hypothesis further states that not only a large part, if not all, of the pre-Cambrian limestones and dolomites, but, as well, the limestones and dolomites of the early Paleozoic formations, are chemical precipitates thrown down by ammonium carbonate. This precipitation grew slower in proportion to the development of the fishes and other efficient bottom scavengers. When the scavenging system became well established, calcium salts could, for the first time, accumulate in the ocean water in excess of the needs of lime-secreting organisms. Thereafter the marine limestones have been largely formed from the débris of the hard parts of animals and plants.

* R. A. Daly, Amer. Jour. Sci., Vol. 23, 1907, p. 93; Bull. Geol. Soc. America, Vol. 20, 1909, p. 153.

The present chapter contains a discussion of various tests of the suggested hypothesis. These include, first, the witness of laboratory experiments; secondly, the testimony of the Black sea—a basin where modern limestone is being deposited by the organic alkali because of the lack of a scavenging system over most of the basin-floor; thirdly, the evidence based on the chemistry of the rivers draining pre-Cambrian terranes; and, fourthly, the lithological evidence of pre-Cambrian sedimentary deposits. In particular, the testimony of the microscope to the chemical origin of thick Cambrian and pre-Cambrian limestones is outlined, and the systematic chemical variation of the limestones through geological time is quantitatively discussed.

This chapter is chiefly a composite reprint of the preliminary papers. The more complete presentation of the hypothesis may be of some value to those who have to do with the paleontology or chemical geology of the pre-Silurian formations. For himself the writer has found more satisfaction in this explanation of the dearth of fossils and in the correlative hypothesis of the dolomites, than in any of the older views on these problems.

Explanations of the Unfossiliferous Character of pre-Cambrian Sediments.

1. *Hypothesis of the metamorphic destruction of fossil remains.*—The view that shells or skeletons were actually once present in anything like the proportions characteristic of Silurian or later marine sediments, and have since been destroyed through either static or dynamic metamorphism, has proved as unsatistory for these pre-Silurian American terranes as it has for pre-Silurian terranes throughout the world. The opposed hypothesis that the hard parts of marine animals were seldom entombed in pre-Cambrian strata is worthy of careful examination. This latter hypothesis is multiple, since it may postulate different causes for the lack of entombment. All postulates must, however, recognize the fact that the mechanical conditions of burial and preservation were all present. So far as chemical composition, detrital composition, rapidity of deposition, etc., are concerned, the sediments of the Cordilleran province, as of other pre-Cambrian formations, are ideal for perfect fossilization.

2. *Brooks hypothesis.*—The admirable essay of W. K. Brooks in the Journal of Geology (Vol. 2, 1894, p. 455), states one conceivable hypothesis. He suggests that the photobathic zone of the sea, where it reached to the bottom, first became inhabited just before Cambrian time. He considers it probable that all the fundamental types of animals from protozoon to mollusc and arthropod, but all as yet soft-bodied, had been evolved in the surface waters of the open sea, far from land. At the close of pre-Paleozoic time the pelagic fauna first discovered the advantages of life alongshore and the special advantages of life on the bottom of the shallow coast-waters. Owing to the intense struggle for existence within the shore zone, there was, in early Cambrian time, a rapid acceleration of development which tended towards the relatively sudden evolution of hard calcareous and chitinous structures, which functioned as means of protection, of offence, or of otherwise perfecting the animals for successful combat. The

fossilization of marine animal types, therefore, first became possible in Cambrian time simply because hard parts had then first become evolved.

A principal and perhaps fatal objection to Brooks's idea is that there is no apparent reason for the long postponement of the 'discovery of the sea-bottom.' We can hardly doubt that, throughout the history of marine life, the shore zone was as accessible to pelagic larvae, etc., as it is now and that the shore zone afforded an advantageous habitat to marine organisms in pre-Cambrian time as at the present. Professor Brooks agrees with most other authorities that the time occupied in the evolution of the soft-bodied but highly diversified pelagic species must have been enormous. It is scarcely conceivable that, in the time taken to evolve such high types as cephalopods and trilobites, the shore zone should not have been long successfully colonized. Skeletal and shell structures should, therefore, have been developed several geological ages before the epoch of high specific differentiation illustrated in the Cambrian. The conclusion seems unavoidable that the sudden appearance of abundant fossils in certain Cambrian beds is not due to a relatively late colonization of the shore zone. Everyone must recognize the value of the shore zone as stimulating the evolutionary process, but the Brooks hypothesis breaks down because it grants an inexplicable postponement of the shore-line's influence.

3. *Suggested hypothesis.*—A third hypothesis may be based on most of the fundamental postulates of biology involved in Brooks's conception. Among these may be specially recalled: (*a*) the very slow evolution of higher animal types from primordial, soft-bodied, simple types; (*b*) the supposition that the bulk of marine animals and plants were, in pre-Cambrian time as now, pelagic and free-swimming; (*c*) the further reasonable supposition that the pre-Cambrian sea was thoroughly tenanted with animals. The point of departure of this third hypothesis lies in the premise that, accepting these three postulates, it was impossible during much of life's evolutionary period for animals to secrete limey structures at all; for *practical physiological purposes* lime salts were non-existent in the sea water for most of the pre-Cambrian life-period.

So far as known to the writer, this hypothesis as a whole has not been stated in geological or biological literature. Macallum has suggested that calcium salts were but sparingly present in the 'earlier Archæan seas,' and notes the possibility that pre-Cambrian organisms could therefore not have acquired the 'lime-habit'; but he gives no explanation of the supposed small content of lime in the sea-water.* Such explanation is the kernel of the hypothesis.

The writer's sincere thanks are due to Mr. R. A. A. Johnston of the Canadian Geological Survey for much help in discussing the basal chemical reactions.

Precipitation of Lime Salts Through the Decomposition of Dead Organisms.

It follows from the main biological postulates of the hypothesis that, in the earliest sea, the higher animal types, including the active hunters and scavengers, were not yet evolved. An important corollary is that the carcasses of countless

* Transactions, Canadian Institute, Vol. 7, 1903, p. 536.

animals living at the surface would, after death, fall to the sea floor, there accumulate and decompose. The rate of decay is in some direct proportion to the temperature. It is in the highest degree probable that the pre-Cambrian polar waters were much warmer than the polar waters are now. Since the bottom temperatures of the whole ocean basin are influenced by polar temperatures, it is fair to conclude that the bottom temperatures of the pre-Cambrian sea were relatively high. Animal carcasses fallen to the sea floor would therefore not be in cold storage but would undergo putrefaction. Both Alexander Agassiz* and Murray† hold that putrefaction takes place even at the present low temperatures of the sea bottom.

During putrefaction ammonium carbonate is given off in large volumes. This powerful alkali has the property of rapidly converting the chloride and sulphate of calcium into precipitated carbonate of calcium. The usual equations for the reactions may be noted:

$$CaSO_4+(NH_4)_2CO_3=CaCO_3+(NH_4)_2SO_4$$
$$CaCl_2+(NH_4)_2CO_3=CaCO_3+2NH_4Cl$$

Both of these reactions are reversible,‡ so that new calcium carbonate introduced by rivers into sea water after the original sulphate and chloride had been converted, would be first changed to the sulphate or chloride and then finally precipitated. According to Murray, Irvine, and Woodhead the first reaction is that according to which a marine animal secretes calcium carbonate shell or skeleton from sea water; in this case the ammonium carbonate is generated in the decomposition of effete products within the body of the animal.§ The chemical process is thus fundamentally the same whether the calcium is abstracted from ocean water through the building of calcareous 'hard parts' or through the precipitation by decaying carcasses. Both actions are doubtless important at the present time.

The precipitation probably occurs chiefly in the bottom stratum of the sea water though it would also proceed during the slow subsidence of decaying carcasses of low density. Diffusion and the vertical interchange of water must tend, in a long period, to remove all the calcium salts from the ocean. At length there would remain in solution only a minute quantity of calcium salts brought into the ocean by the short pre-Cambrian rivers and not yet diffused to the bottom stratum.

Experiment shows that the pure magnesium salts of sea water from which calcium salts have been eliminated are unavailable for the elaboration of carbonate shells and skeletons by organisms, although the organisms live and thrive in such water. Granting that the essential protoplasmic requirements were, in pre-Cambrian time, the same as now, experiments thus show the complete

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* Personal communication.

† Report on the Deep Sea Deposits, Challenger Expedition, 1891, p. 256.

‡ Like hydrochloric acid, most chlorides are practically completely dissociated in dilute aqueous solutions. Analytical Chemistry, by F. P. Treadwell, trans. by W. T. Hall, New York, p. 249, 1905.

§ Proc. Roy. Soc. Edinburgh. Vol. 16, 1889, p. 324, and Vol. 17, p. 79.

possibility of abundant pre-Cambrian marine life in the form of soft-bodied, highly diversified animal types.*

The Eozoic æon was, then, divided into two parts, a long period during which the calcium salts inherited from the Azoic sea were being precipitated, and a much longer period during which the steady evolution of animal types took place in an almost limeless sea.

Duration of the Nearly Limeless Sea.

The conditions suitable for the development of lime-secreting organisms might have been established in three different ways.

Putrefaction on the sea floor has, among its other effects, the generation of much sulphuretted hydrogen by the decomposition of sulphates. The bottom of the Eozoic ocean may have thus been poisoned by the gas in a manner similar to that observed in the world's largest perfect desert, the basin of the Black Sea. The evolution of bottom scavengers or at least the colonization of the general sea bottom, may have been long delayed. Nevertheless, it is possible that the emanation of sulphuretted hydrogen from sea water in which calcium sulphate was almost entirely removed (leaving magnesium sulphate and other sulphates acted on by decaying animal matter as one source of the gas) grew less as time went on, and that the sea-bottom water thereby became gradually sweetened and fit for colonization. The scavenging system once established, it would now be possible for river-borne calcium salts to accumulate in the sea.

Secondly, it is conceivable that the ancient animal types could elaborate limey structures from even the minute quantity of calcium carbonate which sea water can hold in solution, and that these animals did not then need the sulphate or chloride of calcium for the secretion of calcareous structures. Calcium carbonate could not reenter the essential composition of the ocean until the acid radicals freed from the sulphate and chloride (inherited from the Azoic sea) were either destroyed as such or were satisfied by yet stronger bases than lime. The sulphuric acid of the existing seas is being constantly converted into insoluble iron sulphide and free sulphur. This reaction takes place best where ferruginous muds are suspended in the water. It would have but limited effects on the floor of the deep sea far from the pre-Cambrian land. Nevertheless, the whole water-body would, through diffusion and marine currents, be in time affected by the reaction and the sulphuric acid radical of the Eozoic sea would

* At many points in this chapter there is need for a short term designating the entire pre-Paleozoic æon of life-history on the earth. We have no generally accepted word with this meaning. The writer will, accordingly, revert to the term 'Eozoic,' invented nearly forty years ago by Sir J. W. Dawson and later used by him practically to cover the period in question. The term is here employed, however, not in a stratigraphic sense, implying a division of geological time of the same order as the Paleozoic, Mesozoic, etc. It is conceivable that in the future this term may be finally adopted, along with 'Proterozoic' and perhaps other names, to represent one of several 'zoic' divisions of pre-Cambrian time. With this understanding it is hoped that the proposed temporary use of the term 'Eozoic' will occasion no misapprehension. The pre-Eozoic æon of earth-history will be referred to as the 'Azoic.'

be slowly destroyed. How extensively the radical was replaced by the volcanic emanation of sulphurous gases from the earth's interior cannot be demonstrated.

Yet more obscure are the reactions which might have led to the more permanent binding of the sulphuric acid and chlorine radicals to magnesium introduced to the sea in the form of the carbonate by the rivers. The chlorine radical freed from calcium chloride might have become in part gradually bound to sodium.

The utmost efforts of chemists may be unable to determine fully the exact reactions that take place in so complex a solution as sea water, but it seems fair to grant the possibility of some such rearrangements among the ions of the Eozoic sea water. Sodium and magnesium salts are the dominant salts in the sea to-day and it is simplest to suppose that they have become so because of a slow evolution of an ocean tending towards a maximum ionic stability. The sulphates are to-day relatively subordinate because of the very extensive precipitation of insoluble sulphides and carbonates, directly or indirectly through the chemical influences of living or putrefying animals.

If, finally, the acid radicals became either destroyed as such or permanently bound to bases more powerful than lime, the concentration in the sea water of calcium carbonate introduced by rivers first became possible. Then and then only might have been initiated the epoch in which an indefinitely continuous series of lime-secreting animals could be evolved. The beginning of this epoch might have been near the opening of the Cambrian period.

Or, thirdly, we may suppose—and this seems to be the more probable alternative—that a relatively sudden influx of river-borne calcium salts might produce an excess of them in the sea-water solution over that amount which hitherto was kept continuously precipitated by organic decay on the sea bottom. In this case it is simplest to postulate that acid radicals were still free in some measure to convert the river-borne carbonates into sulphates or chlorides. By such reactions the calcium would appear in those salts which are now normally used by lime-secreting animals; the animals would then have a much more abundant source of calcium for the elaboration of hard parts than if the much less soluble carbonate only were present.*

Effects of the Huronian Orogenic Revolution.

Toward the close of Eozoic time there occurred one of the world's greatest mountain-building revolutions. Very extensive mountain-ranges were then (at the beginning of the 'Eparchean Interval') erected, and the continents grew to large size. In a monograph summarizing some of Walcott's researches on the Cambrian formations of North America, that author writes:

> 'The continent was well outlined at the beginning of Cambrian time; and I strongly suspect, from the distribution of the Cambrian faunas upon the Atlantic coast, that ridges and barriers of the Algonkian continent rose above the sea, within the boundary of the continental plateau, that are now

* Cf. J. Murray and R. Irvine. Proc. Roy. Soc., Edinburgh, Vol. 17, 1889, p. 90.

buried beneath the waters of the Atlantic. On the east and west of the continental area the pre-Cambrian land formed the mountain region; and over the interior a plateau existed that at the beginning of, or a little before, Upper Cambrian time was much as it is to-day. Subsequent mountain-building has added to the bordering mountain ranges, but I doubt if the present ranges are as great as those of pre-Cambrian time that are now known only by more or less of their truncated bases. The Interior Continental area was outlined then and it has not changed materially since. Its foundations were built in Algonkian time on the Archean basement, and an immense period of continent growth and erosion elapsed before the first sand of Cambrian time was settled in its bed above them.'†

Following the last world-wide, orogenic paroxysm of pre-Paleozoic time, there was a long interval of more or less perfect baselevelling. In the process thousands of cubic miles of rock were weathered and a large proportion of their mass went, in solution, to the sea. At least three conditions were present to favour a special enrichment of the sea water in soluble salts of calcium. Great volumes of basic volcanic rocks were now for the first time exposed to weathering, with the necessary evolution of lime salts; the thick limestones chemically precipitated in Azoic (?) and earlier Eozoic periods were, now for the first time, exposed to solution in rain water; and the areas of the lands and of drainage basins, with all their assemblage of weathering heterogeneous rocks, were probably greatly increased over their magnitudes in former times.

It is possible to obtain some idea of the quantitative influence of the first two conditions. Hanamann's careful investigation of the Bohemian rivers has clearly shown the important relation between the lithological nature of a terrane and the content of calcium in the waters issuing from the terrane.‡ His results are summarized in the following table in which the figures for each terrane represent averages of several analyses:—

TABLE XXXVIII. *Calcium and magnesium in Bohemian rivers*

Waters from.	*Calcium in parts per million.*	*Magnesium in parts per million.*	*Ratio of calcium to magnesium.*
Granite	7·73	2·33	3·32:1
Phyllite	5·72	2·41	2·37:1
Mica schist	9·33	3·76	2·48:1
Basalt	68·84	19·76	3·49:1
Cretaceous (largely limestone)	33·38	31·36	4·25:1

† C. D. Walcott, 12th Ann. Rep. U.S. Geol. Survey, 1891, p. 562.
‡ Ref. in F. W. Clarke, Data of Geochemistry, Bull. 330, U.S. Geol. Survey, 1908, p. 79; Cf. also A. L. Ewing, Amer. Jour. Science, Ser. iii, Vol. 29, 1885, p. 29.

Since these various waters were working under similar climatic and other solutional conditions, the control of the terrane over the amounts of dissolved calcium and magnesium, is manifest.

After a detailed study of the question Dubois estimates that on an average, *ceteris paribus*, rivers flowing entirely over silicate rocks carry only one-tenth as much calcium carbonate as rivers flowing entirely over limestone and remarks that even this fraction is almost certainly too large. According to his estimates only one-thirtieth of the calcium carbonate annually entering the sea by the rivers has been newly formed through the decomposition of silicates. The rest is derived from the direct solution of limestone. He has further concluded that in early Archean time the world's river-system probably carried not more than one-eight as much of the carbonate to the ocean as the existing river-system carries.§

Merely from the quantitative studies of Hanamann and Dubois we may hold, with much confidence, that the annual supply of calcium to the ocean after the revolution was from two to five or more times that characteristic of earlier Huronian and pre-Huronian time.

The revolution must have had another important effect—in decreasing the sea-bottom area on which the precipitation of calcium carbonate took place. The researches of the 'Challenger' and other oceanographic chemists show that at depths greater than 3,000 fathoms little or no solid calcium carbonate can remain on the sea floor. In fact, the tendency to the complete solution of this salt is strong at all depths greater than 2,500, if not 2,000 fathoms. This means that the permanent removal of calcium carbonate from the present oceanic solution through the decay of animal carcasses at the bottom seems to be possible only in about one-half of the existing ocean basin—say 70,000,000 square miles. This area is partly neritic (depths less than 200 fathoms) and partly bathyal (depths between 200 fathoms and 2,000 fathoms). On account of the higher temperatures and lower bottom pressures (pressure increasing the solubility of the carbonate) of the shallower water, we should expect the rate of chemical precipitation of calcium carbonate at the bottom to be concentrated in the neritic (epicontinental) and shallower bathyal regions, a total area of about 35,000,000 square miles.

Let us assume that previous to the Huronian orogenic revolution the whole area of the lands was 20,000,000 square miles, or about 20/55 of the present area. On the view that the ocean has had a nearly constant volume from Huronian times to the present, it follows that the early Huronian sea was largely epicontinental for an area of more than 35,000,000 square miles; so that the area of rapid chemical precipitation of calcium carbonate was about twice as great as the possible present area. Let us also assume that the Huronian revolu-

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§ E. Dubois. Proc. Section of Sciences, Kon. Akad. van Wetenschappen, Amsterdam, Vol. 3, 1901, pp. 119-126.

tion increased the land area to 55,000,000 square miles, which is roughly the present area of the lands.*

The annual rate of the supply of calcium to the ocean was, on these assumptions, increased from (55/20×2=) 5·5 to (55/20×5+=) 14 + times by the late-Huronian crustal movements. But the sea-bottom area over which the chemical precipitation of calcium carbonate was compelled was halved by those movements. Thus the post-Huronian conditions favouring the possibility that a part of the river-borne calcium could remain in solution in the ocean were from (5·5×2=) 11 to (14×2=) 28 or more times more effective than the pre-Huronian conditions.

Although little stress can be laid on any particular figure embodied in the foregoing conclusions, this rough analysis serves to illustrate the strength of the probability that the prodigious crustal movements of the late-Huronian and pre-Cambrian interval made a comparatively rapid and quite drastic change in the chemical condition of the ocean.

Analyses of the Ottawa River.

The view that the supply of calcium to the ocean reached a maximum rate toward the close of pre-Cambrian time is based on some speculation. Apparently more certain are the grounds for believing that the late pre-Cambrian ocean could have received an annual calcium supply which was only a small fraction of the present annual supply. The belief may be founded on a comparison between the analyses of rivers now draining large pre-Cambrian areas with the analyses of rivers draining average terranes of the present continents.

Few rivers are more typical of the former class than the Ottawa above Ottawa city. Its thousands of miles of trunk and branch channels are sunk in the largest pre-Cambrian area of the world, and it happens that most or all of the recognized rock types of the pre-Cambrian formations are liberally represented in its drainage basin. Only very small and practically negligible masses of younger rocks occur in the basin above the city of Ottawa.

At the request of the writer, Mr. F. T. Shutt, chemist to the Dominion experimental farms, has very kindly made two analyses of the Ottawa water, taken at the Chaudiere falls, which face the city. The first sample was collected on March 12, 1907, at a time when the river was still ice-covered and reported to be at the lowest stage known in fifty years. The second sample was collected on July 16, 1907, during the summer high-water period. Its analysis is more

* Joly's well known estimate of the age of the ocean as about 90,000,000 years seems much too low for the needs of the geologists. His view that the sodium borne into the ocean by the rivers during past time is nearly all represented in the present sea-water is apparently one of the soundest in dynamic geology. The chief source of doubt as to the validity of his method of calculation consists in the obvious fact that it is not yet possible to secure even an approximate idea as to the secular variation of the land area in size. The age of the ocean would be greatly increased if account be taken of a relatively small area throughout much of pre-Cambrian time. To the present writer, Joly's estimate is of value in suggesting that the pre-Huronian land area was in reality small.

complete than that of the first sample. The two gave results shown in Columns 1 and 2 of Table XXXIX:—

TABLE XXXIX.—*Analyses of Ottawa river.*

	1 Low water.	2 High water.
	Parts per million.	*Parts per million.*
Total solids at 98-100° centigrade	54·66	46·07
Loss on ignition	24·03	15·74
Solids after ignition	30·63	30·33
SiO_2	6·52	7·06
Al_2O_3	·38	·52
Fe_2O_3	·34	·70
MgO	3·87	2·77
CaO	12·57	8·18
Na_2O	not det.	2·14
K_2O	not det.	·67
SO_3	3·70	2·51
Mn_3O_4	not det.	·86
P_2O_5	not det.	·43
Cl	not det.	·50

Five sanitary analyses of the Ottawa river water have been made by Mr. Shutt. The samples were taken on the following dates: December 22, 1887; October 18, 1898; December 7, 1898; May 8, 1899; and August 22, 1905. These analyses gave respectively total solids at 53.0, 55.6, 42.4, 48.8, 62.4 parts per million, and solids after ignition (December 22, 1887, not determined), 34.0, 28.0, 22.8, 36.4 parts per million. The figures average 52.4 parts per million for total solids and 30.3 parts per million for solids after ignition. It will be seen that the variation in each of the two quantities from year to year and from season to season is relatively small; hence we may conclude that the two 1907 analyses fairly represent the average nature of the Ottawa river water in modern times.

The content of calcium and magnesium of the two stages of the river, and their mean have been calculated to parts per million and the results entered in Table XL., which also gives, for purposes of comparison, the calcium content of other rivers as well as of the Ottawa river at Sainte Anne rapids below the solid block of Paleozoic limestones lying between Ottawa and Montreal. The references for the original publications of these latter analyses may be found on page 60 of Bulletin number 330 of the United States Geological Survey:—

TABLE XL.—*Calcium and magnesium in various rivers.*

River.	Terrane.	Calcium.	Magnesium.	Ratio of Ca to Mg
		Parts per million.	*Parts per million.*	
Ottawa—				
a. Low water	Late pre-Cambrian	8·98	2·35	3·50 : 1
b. High water	"	5·84	1·67	3·82 : 1
c. Mean of *a* and *b*		7·41	2·01	3·69 : 1
d. Sainte Anne	Late pre-Cambrian and early Paleozoic.	9·92	2·02	4·91 : 1
Average of four Swedish rivers and Ottawa and Pigeon rivers.	Late pre-Cambrian	6·88	1·52	4·52 : 1
Saint Lawrence at Ogdensburg—average of 6 monthly analyses.	Late pre-Cambrian and Paleozoic	32·05	7·21	4·44 : 1
Mississippi—				
a. At Minneapolis — average of 23 analyses.	Late pre-Cambrian and early Paleozoic.	41·18	15·34	2·69 : 1
b. Memphis—analyses of 17 composites.	Late pre-Cambrian and Paleozoic chiefly.	34·38	13·75	2·50 : 1
c. New Orleans — average of 52 composites.	Nearly average continental mass of present time.	33·90	8 65	3·92 : 1
Danube—average of 23 analyses.		43·89	9·94	4·42 : 1
Rhone—average of 5 analyses		44·91	6·22	7·22 : 1
Seine		73·99	1·60	46·24 : 1
Average of 19 rivers (Murray)*	ditto	33·85	7·75	4·37 : 1
Average of 44 rivers	ditto	37·77	9·03	4·18 : 1

* Sir John Murray: Scottish Geographical Magazine, Vol. 3, 1887, p. 65.

COMPARISON OF THE OTTAWA AND OTHER RIVERS.

The Ottawa carries past Ottawa city only 23 per cent as much calcium per volume as the Saint Lawrence river carries past Ogdensburg, and less than 20 per cent as much calcium per volume as the Mississippi carries past Minneapolis. About one-third of the Saint Lawrence basin is occupied by the Great lakes, in which area probably very little solution of calcium salts is taking place. Another large part of the basin is occupied by the pre-Cambrian terranes where highly calcareous rocks are relatively rare. The content of this river is therefore less than it would be if the river basin were all occupied by the average rocks of the whole continental area of the earth. The comparison of these three rivers is specially instructive, since they are all working under essentially similar climatic conditions, with nearly the same ratio of rainfall to run-off. From the comparison it seems probable that, if the continents were all of their present size and composed of rocks typical of the lands during the late pre-Cambrian, the rivers would deliver to the sea annually not more than one-fifth as much calcium as is carried by the existing rivers of the continents.

This conclusion becomes more convincing when the Ottawa water is compared with the other rivers noted in Table XL.

In Clarke's admirable compilation of river analyses those referring to rivers which drain pre-Cambrian terranes throughout their respective basins are five in number, including the Pigeon river of Minnesota and four rivers in Sweden. The average content of calcium (and of magnesium) in these rivers, together with the Ottawa at Ottawa city, is stated in the table. It will be seen that the proportion of calcium is very close to that in the Ottawa alone. We have, therefore, corroboration for the view that the Ottawa is a good world type of rivers draining late pre-Cambrian terranes.

On the other hand, the Mississippi at New Orleans must be regarded as one of the best types of rivers draining the average terranes of the present continents. From Murray's average of nineteen rivers the present writer has calculated the proportions of calcium (and magnesium) and has also (using Clarke's compilation) calculated the contents of these elements in forty-four of the largest rivers of the globe. In this second computation the individual analyses were roughly weighted according to the areas of the respective river basins. The result is believed to give a truer idea of the average content of calcium in the world's rivers than does Murray's estimate.

The results seem to show that the average world river, working on the average terrane and under average climatic conditions, carries about the same proportion of dissolved calcium as the average water of the Saint Lawrence at Ogdensburg and the Mississippi above Minneapolis. The table indicates that the influence of the terrane is dominant and the influence of climate subordinate, in their respective control over the content of calcium.

The Mississippi above Memphis drains rock formations which together make fairly good equivalents of the average Mesozoic and Cenozoic land areas. So far as the influence of the average world terranes is concerned, the Mesozoic and Cenozoic rivers were enriched in calcium about as much as the existing world rivers. The early Paleozoic rivers were, on the average, probably not much richer in calcium than the late pre-Cambrian rivers. The control of the Paleozoic terranes on the calcium content of the Ottawa itself is shown by the contrast between the Ottawa city analyses and that at Sainte Anne near Montreal. Even a few hundred square miles of Upper Cambrian and Ordovician rocks (largely limestones) below Ottawa city makes the calcium content materially rise.

Chemical Contrast of pre-Cambrian and later River Systems.

In spite of the complexity of the whole problem, we may fairly conclude that if, in the late pre-Cambrian time, the land areas were of their present size, the ocean then received annually only a small proportion—probably less than one-fifth—of the calcium supplied each year by the present rivers. A contrast of the same order must have existed between the calcium content of the late pre-Cambrian rivers and the rivers characterizing most of Mesozoic and Cenozoic time.

If the late pre-Cambrian lands had a total area but one-half as great as the present total land area, the rivers may have carried annually to the sea less than 10 per cent of the amount of calcium now carried to the sea by the world's rivers.

This estimate obviously involves the assumption that the pre-Cambrian rate of chemical denudation was no more rapid than the present rate. Since the rate is controlled (apart from the influence of the terrane) principally by the abundance of the organic acids attacking the bedrock, we may well suppose that the well vegetated Ottawa river basin is witnessing solution at as rapid a rate as in late pre-Cambrian time. It might be considered that a tropical temperature during the pre-Cambrian would have caused specially rapid solution of the rocks at that time. This view is, however, hardly supported by an inspection of the data relating to existing tropical and extra-tropical rivers. Furthermore, the recent glaciation of the Ottawa basin has caused the removal of secularly weathered rock, so that the formations now exposed to erosion contain nearly their original amount of soluble matter. For this reason the calcium content of the existing river may be near its possible maximum for a region of average rainfall.

Without further entering upon this confessedly obscure subject, we may retain the foregoing estimate as indicating the order of magnitude in the contrast between the late pre-Cambrian and present supply of calcium to the ocean through weathering and river inflow.

Variations in the Calcium Supply during and after the pre-Cambrian.

Before the Huronian revolution the supply of river-borne calcium to the ocean was almost certainly less than one-fifth as rapid as it is to-day, and it may have been less than one-twentieth as rapid, while the amount of animal matter completely decaying on the sea floor, and therewith the likelihood of the precipitation of calcium salts, may have been, respectively, thousands of times greater than they are now.

Immediately after the Huronian revolution and during the immensely long period of baselevelling which followed it, the annual supply of calcium to the ocean may have approached rivalry with the present annual supply. The supply doubtless diminished somewhat as more and more of the Huronian and pre-Huronian limestone and basaltic areas were lessened by erosion and as the Laurentian granite batholiths were uncovered and exposed to solution; but this change must have been very slow, and it did not annul the critical effect of continental enlargement. During the long erosion cycle the ocean was, for the first time, specially enriched in river-borne calcium salts.

First Calcareous Fossils.

This special influx of calcium salts may be conceived as keeping the surface layers of the sea water sufficiently supplied with calcium for the needs of lime-secreting organisms, while the bottom layers lost their calcium content by precipitation of the carbonate of calcium. Such contrast of surface and bottom water would be due to the slowness of diffusion through a body of liquid so great as the ocean. Under the conceived conditions the most favourable places for the invention of calcareous hard parts would be, possibly, localized areas, such as the open sea opposite the greater river deltas, or such as the epicontinental seas more or less isolated during the orogenic revolution. The slow spread of the scavenging system may already have had some effect in the late pre-Cambrian, thus increasing the chances that some calcium could remain in the oceanic solution.

Since Lower Cambrian time the continents have in part undergone submergence and emergence, but they have doubtless never resumed their small total area characteristic of the pre-Huronian period. In any case we have obvious proofs that the ocean has, since the Cambrian, contained enough calcium for the needs of lime-secreting organisms, and the natural explanation is to be found in river inflow.

The invention of chitinous exoskeletons (which, themselves, in Cambrian types, contain some lime carbonate or phosphate and were preserved for that reason) furnishes the link between the soft-bodied Eozoic animals and the post-Cambrian dominant species armoured with calcium carbonate. The Cambrian brachiopod shells are often similarly chitinous and offer other illustrations of the link between these two principal organic epochs.* The unique and permanent change in the oceanic composition made possible the dominance of post-Cambrian molluscs, brachiopods, etc., and made also possible the preservation of countless post-Cambrian fossils.

Following our main hypothesis, the chief animal fossils expected in Eozoic rock are impressions of soft-bodied species, the tests of siliceous organisms, and chitinous tests. The last will be expected in the higher beds of the series and should owe their preservation to limey ingredients secreted by the animals inhabiting the late Eozoic sea. Along with the chitinous fossils may be a few calcareous shells or skeletons also evolved because of the late Eozoic enrichment of the sea in river-borne lime salts. These are, in fact, the kinds of fossils discovered in the pre-Cambrian rocks by Walcott, Barrois, Cayeux and others. For obvious reasons fossils of all four classes must be few or else difficult to discover in the rocks. The very presence of the impressions of medusæ in rocks as old as the Lower Cambrian strengthens the suspicion that the metamorphic hypothesis cannot explain the absence of calcareous shells or of their impressions in many thousands of feet of equally little metamorphosed Eozoic sediments. The impression of a shell is assuredly more likely to be preserved in mud or sand than is the impression of a medusoid animal. It seems, on the other hand, certain that the pre-Cambrian rocks of the North American Cordillera never at any time contained any considerable number of calcareous shells or skeletons. The same conclusion applies in some measure to the Cambrian rocks of the British Columbia-Montana section.

In passing, it may be remarked that one fundamental idea of the hypothesis, namely, the variation of the amounts of calcium salts dissolved in the ocean in different geological periods, may possibly be of use in helping to explain the rise, culmination, and extinction of certain faunal groups. For example, the immense development of the ammonites both in numbers and in their unequalled

* J. D. Dana, Manual of Geology, p. 486, 1895.

elaboration of shells, may be correlated with the special enriching of the ocean in calcium salts during the Permian and following pre-Triassic time. In that long period the land areas were of extraordinary size and were largely covered with thick Paleozoic limestones exposed for the first time. The impoverishment and final extinction of the ammonites may have been largely caused by the partial exhaustion of the calcium content of the ocean during the long and remarkably extensive submergence of the continental plateaus during the Cretaceous. To such geographical and chemical changes, the ammonites, most of which were possibly pelagic species (all of them needed abundant supplies of calcium salts), must have been peculiarly sensitive, while the coastal species, being nearer the sources of calcium-supply (the river-mouths), would be living under more equable conditions.

Tests of the Suggested Hypothesis.

The rearrangement in the chemical constituents of pre-Cambrian ocean water through the decay of animal matter is the fundamental premise of the hypothesis and it deserves special examination and illustration. The tests of the premise are at least threefold: laboratory experiment, observations on existing seas, and the witness of pre-Cambrian deposits, particularly of the carbonates.

CORROBORATIVE EXPERIMENTS.

Murray, Woodhead, and Irvine have made a number of valuable observations on the chemical modification of sea water exposed to the emanations of putrefying animal matter and to the effete substances derived from living animals.*

In one experiment four small crabs weighing 90·72 grams were placed in sea water absolutely free from carbonate of lime. After twelve months they produced an alkalinity in the water equal to the production of 45·36 grams of calcium carbonate. This effect was due to the decomposition of calcium sulphate by the uric acid, urea, and other effete matter.

In a second experiment it was found that in seventeen days and at temperatures ranging from sixty to eighty degrees Fahrenheit, the decomposition of urine mixed with sea water had precipitated practically all the sulphate of lime present. A similarly complete precipitation of all the sulphate in a solution of pure water and calcium sulphate present in the proportion of average sea water, was effected in eleven days by the decomposition of urine added to the solution.

In a fourth experiment, nine small crabs were placed in two liters of water, where they died. Complete putrefaction set in and continued at temperatures varying from seventy to eighty degrees Fahr. Analysis showed that all the lime salts were precipitated in the form of the carbonate.

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* Proc. Royal Society Edinburgh, Vol. 17, 1889, p. 79.

Steinmann has made important experiments which tend to corroborate some of the main conclusions of Murray and his colleagues. He added decaying albumen to solutions of calcium chloride and found that calcium carbonate, in the form of round, minute bodies like coccoliths, was precipitated. This result raises the query whether many of the coccoliths described as occurring in deep-sea sediments are not direct witnesses to an actual chemical precipitation of calcium carbonate on a large scale over much of the sea floor.

Irvine and Woodhead have shown conclusively that marine animals, even those normally secreting limey structures, will live and comparatively thrive in sea water from which every trace of calcium carbonate has been eliminated.† In one experiment they mixed sodium chloride, magnesium chloride, magnesium sulphate, calcium sulphate, and potassium sulphate with pure water in about the proportions of average sea water. In this artificial sea water (No. 1) they placed a number of crabs. In their proper seasons the exoskeletons were shed but were never rebuilt by the animals. Yet the crabs continued to feed and live, long after the exfoliation had taken place.

In a second experiment ·0903 per cent by weight of calcium chloride was added to No. 1 water, giving No. 2 water. In this the crabs lived and rebuilt their exoskeletons. This new structure was composed of the carbonate and phosphate of lime and chitinous matter in the proportions present in normal shells. Other crabs similarly throve in a third water in which the calcium chloride in average sea-water proportion was substituted for the calcium sulphate of No. 1 water.

The proof is clear that the secretion of calcareous structures is by no means dependent upon the presence of calcium carbonate in sea water.

In a fourth experiment sodium chloride and magnesium chloride were dissolved in pure water in the proportions of average sea water. Crabs and fish were found to thrive in this water, 'feeding greedily, but of course ecdysis (elaboration of cast exoskeletons) in such water was impossible.' Ecdysis was, however, carried out when calcium chloride was added to the solution.

The whole series of experiments cited indicate the possibility, first, that the pre-Cambrian ocean could hold but a minute quantity of lime salts in solution unless those salts were being continually and largely fed into the sea and preferably fed at the surface, farthest from the bottom stratum of water charged with the products of decaying animal matter; and, secondly, that abundant life existed in water so nearly limeless.

OBSERVATIONS ON THE BLACK SEA.

The well known, remarkable studies of Andrussow and others on the hydrography and deposits of the Black Sea show that we have in a large existing basin a strong analogy to the imagined Eozoic

† R. Irvine and G. S. Woodhead, Proc. Royal Society, Edinburgh, Vol. 16, 1889, p. 324.

ocean.* As a result of a special series of geological events, this sea basin is devoid of bottom scavengers over the greater part of its area. On the other hand, the surface fauna has always been abundant. The bottom has therefore received the fallen carcasses of the surface animals which, unceasingly, have putrefied in the relatively high temperature of that sea floor. Two soluble products, ammonium carbonate and sulphuretted hydrogen, have been generated in enormous quantities at the bottom. The gas has poisoned the water from the greatest depth (1,227 fathoms) to the level of about 100 fathoms from the surface. Below the 100-fathom level no life is possible except that of a few anaërobic bacteria, one of which has been studied and named as the primary cause of putrefaction.

Corresponding to our hypothesis, it has been found that the bottom muds of the Black Sea basin are rich in a powdery deposit of carbonate of calcium. Far from shore, and thus in areas not so abundantly supplied with silts, the carbonate occurs in thin white layers. In shallower water, from '300 to 717 fathoms,' the mud is black and the presence of the carbonate is masked by the relative increase of mechanical deposit.

The black muds, and less conspicuously the deposits of the greater depths, are strongly charged with disseminated iron sulphide. The mode of formation of this sulphide is summarized by Murray and Irvine in the following equations:

$$RSO_4 + 2C = 2CO_2 + RS$$
$$RS + 2CO_2 + H_2O = H_2S + RCO_3CO_2$$
$$RS + RCO_3CO_2 + H_2O = 2RCO_3 + H_2S$$
$$Fe_2O_3 + 3H_2S = 2FeS + S + 3H_2O$$

These reactions presuppose the absence of free oxygen. Andrussow points out, not only the incompatibility of oxygen and free sulphuretted hydrogen, but also states another cause of the poverty of the bottom waters in free oxygen. It is in part due to the lack of normal vertical currents in the Black Sea; these are impossible because of the peculiar density stratification of this basin.

The equations show that, in the presence of ferruginous muds, free sulphur is precipitated along with the sulphide of iron. It is thus easy to understand the formation of the numerous nodules of iron pyrites found in the black muds. In the main ocean near muddy shores the foregoing reactions also apply to a part of the changes produced by putrefaction. The analogous case of the Black Sea, therefore, proves the truth of the prevailing views as to the formation of iron pyrites in marine sediments, and also the corollary of our hypothesis as to the gradual destruction of the sulphuric acid radical in Eozoic sea water. That all the lime salts have not been precipitated from the Black Sea water is, of course, due to the large amount of Mediterranean water constantly renewing the lime salts by way of the bottom current at the Bosphorus.

It seems clear that the Black Sea is carrying on a gigantic natural experiment which strengthens belief in the main deductions so far made as to the physical and biological conditions of the Eozoic sea. In one important respect

* Guide des Excursions, VIIme Congrés Géologique Internationale, No. 29, 1897.

the analogy breaks down; we shall see that, after all the lime salts are removed from sea water, the ammonium carbonate has special power to attack the magnesium salts. This fact cannot, for the reason just stated, be illustrated in the case of the Black Sea.

PRE-CAMBRIAN SEDIMENTARY DEPOSITS.

A third test of the hypothesis consists in an examination of actual rock-deposits in the pre-Cambrian.

Origin of Dolomite and of Other Magnesian Sediments.—It is an established fact that dolomites and magnesian limestones, sandstones, and argillites are very common in pre-Cambrian rock series. Granting that Eozoic organisms could not secrete magnesium carbonate shells or skeletons, it follows that the magnesian content of these rocks must have had a chemical origin.

The magnesium carbonate was not thrown down simply because this little soluble salt, as it was introduced by the pre-Cambrian rivers, saturated the sea water. Then as now calcium carbonate was doubtless much in excess of magnesium carbonate in river waters. We have seen that the acid radicals set free in the persistent precipitation of calcium carbonate, would, during Eozoic time, prevent the permanent solution of magnesium carbonate in any appreciable quantity. On the other hand, we must conclude that the long-continued precipitation of magnesium carbonate was effected by the action of a strongly alkaline carbonate. We are thus naturally led to the discussion of the possible precipitation of magnesium carbonate also by the ammonium carbonate emanating from decaying animals.

The experiments on this subject are, at first sight, contradictory. Linck has recently shown that when ammonium carbonate is added to sea water, aragonite is precipitated but no magnesium carbonate was found by him in the precipitate.* On the other hand, Pfaff, using an artificial sea water similar in composition to average sea water, found that, after a certain interval of time a part of the magnesium in the salts was thrown down as the basic carbonate while there was an abundant precipitation of calcium carbonate.† Pfaff's result accords with the general experience of analytical chemists; hydrous magnesium carbonate will be precipitated by the alkaline carbonate *if time enough* be allowed.

The reactions for magnesium sulphate and chloride commonly assume the following forms:—

$$4MgSO_4 + 4(NH_4)_2CO_3 + H_2O = Mg_4(CO_3)_3(OH)_2 + CO_2 + 4(NH_4)_2SO_4$$

and

$$4MgCl_2 + 4(NH_4)_2CO_3 + H_2O = Mg_4(CO_3)_3(OH)_2 + CO_2 + 8NH_4Cl.$$

The presence of ammonium chloride tends to prevent the precipitation of the carbonate from a solution of magnesium chloride; it is important, therefore, to

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* G. Linck, Neues Jahrbuch für Mineralogie, etc., Beilage Band, xvi, p. 502, 1903.
† F. W. Pfaff, Neues Jahrbuch für Mineralogie, etc., Beil. Bd., Vol. ix, p. 504, 1894.

note the fact that ammonium chloride formed in this way at the sea bottom diffuses away to upper strata of the ocean waters and would not interfere with the final completion of the reaction.

Besides the element of time and the undoubted presence of an appreciable amount of magnesium salts in the pre-Cambrian sea, another principal factor must be considered. Hunt has shown that the precipitation of magnesium carbonate from sea water by alkaline carbonates is facilitated if the calcium salts be removed. Our hypothesis states that the latter were absent from the bottom stratum through most of Eozoic time.

Again we may turn to the noteworthy experiments of Murray and Irvine for a suggestion of the truth of the foregoing statements. Their table is here reproduced (No. XLI). It shows the composition of the precipitate thrown out of a mixture of sea water and urine after standing seven days, the urine meanwhile decomposing and furnishing the alkaline carbonate:—

Table XLI.

Water and organic matter containing ammonia (7·38 p.c.)	31·81
Carbonate of lime	4·85
Phosphate of magnesia and ammonia	51·10
Phosphate of lime	12·24
	100·00

Table XLII. shows the composition of the precipitate thrown out of the mixture (after filtration from the precipitate which was thrown out in seven days), standing other ten days:—

Table XLII.

Water and organic matter	20·25
Carbonate of lime	75·35
Carbonate of magnesia	1·02
Phosphate of magnesia	3·38
	100·00

These tables* prove that the magnesium carbonate came down only after much, perhaps nearly all, of the calcium was precipitated as carbonate. It should also be observed that a considerable amount of the precipitating alkali, ammonia, was removed from the mixture in the first precipitate.

Murray and Irvine have also investigated the composition of the water filtered out of the mud dredged from the bottom in Granton Harbour and also near the Forth Bridge.† The following table gives the resulting total analysis of the salts of the average mud-water and also bears a column indicating the analysis of average sea water:—

* J. Murray and R. Irvine, Proc. Roy. Soc. Edinburgh, Vol. 17, 1889, p. 104.
† Trans. Royal Society Edinburgh, Vol. 37, 1895, p. 490.

	Average Sea-water.	Mud-water.
Sodium chloride	77·758	79·019
Magnesium chloride	10·878	11·222
Magnesium bromide	0.217	0·220
Magnesium sulphate	4·737	3·232
Potassium sulphate	2·365	2·506
Ammonium sulphate	....	0·206
Magnesium carbonate	....	0·909
Calcium carbonate	0·345	2·686
Calcium sulphate	3·600	....
	100·000	100·000

In the mud-water calcium sulphate is absent, magnesium sulphate is deficient when compared with average sea water; calcium carbonate is increased, and magnesium carbonate and ammonium sulphate are both present. The high chlorides show that the carbonates are not in excess because of fresh-water inflow. The ratio of magnesium carbonate to calcium carbonate is 1:3. When the clear water filtered from the mud was boiled for a short time, a crystalline precipitate was thrown down, consisting of 73·3 per cent calcium carbonate and 26·7 per cent magnesium carbonate. The formation of both carbonates is ascribed by Murray and Irvine to the reaction of ammonium carbonate chiefly on the sulphates, a conclusion which cannot be doubted, especially in view of the presence of ammonium sulphate in the mud-water. The alkaline carbonate was, of course, derived from decaying animal matter contained in the muds.

These different experiments teach that hydrous carbonate of magnesium can be precipitated by ammonium carbonate emitted from decaying animal remains; that the precipitation is much slower than in the case of calcium carbonate and is retarded by the presence of calcium salts in the solution. We thus see how, in the nearly limeless sea water of pre-Cambrian time, the proportion of precipitated magnesium carbonate would be high, even, possibly, approaching the ratio in true dolomite. Indeed, it is quite possible that precipitates of pure basic carbonate of magnesium later changed to magnesite, were formed in those places in the sea basin where the calcium salts were completely absent from the oceanic composition.

On the other hand, the abstraction of magnesium from the pre-Cambrian water may have followed a process analogous to that which may be actually observed in the boring at the Funafuti atoll.* Crystals of dolomite may have grown on or near the surface of the pre-Cambrian bottom mud, much as they are now growing in the buried (porous) coral rock of the atoll.

Clearly our ideas must not be too rigid regarding the detailed history of these early magnesian deposits. We cannot say how far the sea waters in which animal life first began were charged with magnesium salts. We cannot say how far these and the other salts brought in by the early rivers contributed to the formation of the extensive dolomites and magnesium limestones known to occur in pre-Cambrian terranes. Our hypothesis holds that the

* The Atoll of Funafuti, published by the Royal Society, London, pp. 392, 413, etc.

calcium carbonate of the dolomites and of the pure calcium-limestones was, for most of the Eozoic æon, introduced to the sea by the rivers. Notwithstanding the slowness of the precipitation of magnesium carbonate at ordinary temperatures, some excess of magnesium salts in solution in that sea might easily permit the basic magnesium carbonate to be thrown down in very high proportion when compared with the precipitate of the other carbonate. What determined the actual composition of any one bed cannot be declared. Opposite the mouth of a large river we might expect beds of practically pure calcium carbonate. Far from shores the chemical deposit would be more magnesian. Gradual changes in the rivers, in the marine currents, or in the configuration of the coast-line would cause alternations in the composition of the precipitate, the magnesium component rising or falling according to the highly variable circumstances. The beds would further be indefinitely varied according to the proportion and kinds of mechanical detritus intermixed with carbonates. Eozoic sediment may be fetid to-day because of the residual animal matter imprisoned in such detritus and chemical precipitate.

When calcium salts, at or about the beginning of Cambrian time, came into permanent excess in sea water (i.e., excess over the needs of lime-secreting organisms), the precipitation of magnesium carbonate became more difficult, but this change would be extremely slow. Even at the present day the proportion of lime salts in sea water is low. The existing rivers are nearly the greatest rivers the world has known, so far at least as drainage basins are concerned. Those rivers flow through immense tracts of limestone and dolomitic formations which evidently did not furnish carbonate to rivers of Paleozoic or Mesozoic age. It is clear that Paleozoic and Mesozoic rivers may have sent even less sulphate and carbonate of calcium into the sea than is now being poured into it. We should, therefore, expect that, during the Paleozoic and Mesozoic æons, there was a less abundant precipitation of magnesium carbonate than during the Eozoic, but a more abundant precipitation than at the present time.

Average Ratio of Calcium to Magnesium in the Limestones of the Different Periods.—The writer has attempted to test these conclusions quantitatively. For this purpose nearly 900 analyses of types of pre-Cambrian, Paleozoic, Cretaceous. Tertiary, and Quaternary-Recent limestones have been calculated, so as to show the average ratio of calcium to magnesium throughout the series. The analyses were taken from the government survey reports of Canada and the United States; from Logan's 'Geology of Canada'; from the state survey reports of Arkansas, Indiana, Iowa, Kentucky, Minnesota, Ohio, Pennsylvania, West Virginia, and Wisconsin; from the reports of the Ontario Bureau of Mines; from Firket's elaborate paper on the limestones of Belgium,* and from the list of analyses supplied for this report.

The selection is far from being as complete as it might be made, but it is believed that enough analyses are represented to give a fairly accurate idea of the variation of the ratio through geologic time. The number of pre-Cam-

* A. Firket: Annales Société Géologique de Belgique, Vol. 11, 1883, p. 221.

brian and Cambrian limestones averaged is, in both cases, low, but includes nearly all that seemed to be available. The number of the Tertiary and later limestones averaged is again low, but the labour of searching for additional ones did not seem necessary, since it is well known that these later limestones are usually very low in magnesium. Lesley had already prepared a remarkable series of analyses (230) which was intended to afford the average ratio for the Ordovician limestones of Pennsylvania. This result could not, however, be safely used, inasmuch as the whole series refers only to some 370 feet of beds out of several thousand feet of the limestones locally developed, and at that represents only a local phase of the Ordovician.† It has thus seemed better to use the analyses derived from many Ordovician formations in Canada and the United States. The ratio for the pre-Cambrian may be a little too high, for the reason that thirty-three out of the sixty-one analyses selected were taken from Miller's Bureau of Mines report on the limestones of Ontario, in which there was some tendency to select limestones specially adapted to lime burning. Excluding twelve analyses of specimens from limekiln quarries in Ontario, the average ratio for the remaining pre-Cambrian rocks is 3.61 : 1.

The results of the compilation and calculation are given in Table XLIII:—

TABLE XLIII.—*Calcium and magnesium in limestones of the geological periods.*

Period.	1. Number of analyses averaged.	2. Ratio of $CaCO_3$ to $MgCO_3$.	3. Ratio of Ca to Mg.
Pre-Cambrian.			
a. From N. America except those in *b*	28	1.64 : 1	2.30 : 1
b. From Ontario (Miller)	33	4.92 : 1	6.89 : 1
c. Average of *a* and *b*	61	2.93 : 1	4.10 : 1
Cambrian (including 17 of the Shenandoah limestone)	30	2.96 : 1	4.14 : 1
Ordovician	93	2.72 : 1	3.81 : 1
Silurian	208	2.09 : 1	2.93 : 1
All pre-Devonian	392	2.39 : 1	3.55 : 1
Devonian	106	4.49 : 1	6.29 : 1
Carboniferous	238	8.89 : 1	12.45 : 1
Cretaceous	77	40.23 : 1	56.32 : 1
Tertiary	26	37.92 : 1	53.09 : 1
Quaternary and Recent	26	25.00 : 1	35.00 : 1
Total, 865.			

† J. P. Lesley: Final Report of Pennsylvania Survey, Vol. 1, 1892, p. 327.

It will be observed that the ratio of calcium to magnesium is fairly constant for all the (392) pre-Devonian analyses, in which the average is 3.35 : 1.* The ratio abruptly rises in the Devonian and increases rapidly in the Carboniferous. The Cretaceous shows an apparent maximum but it is quite possible that a larger number of analyses of Tertiary and later formations would give average ratios at least as high as that of the Cretaceous.†

The ratio for the pre-Cambrian limestones (3.61 : 1 to 4.10 : 1), like that of all the pre-Devonian, is significantly close to the ratio of calcium to magnesium in the Ottawa river analyses made at the capital (low water stage, 3.82 : 1; high water stage, 3.50 : 1; their average, 3.69 : 1). This comparison of itself suggests that, during the pre-Devonian time, the river-borne magnesium and calcium were wholly precipitated after diffusing to the sea bottom. In fact, the correspondence must be regarded as giving powerful support to the hypothesis.

The abrupt change in passing from the Silurian to the Devonian may, perhaps, be referred to the development of the fishes during the early Devonian. This development doubtless began in relatively shallow water, and the flesh-eating and scavenging fishes must have aided greatly in preventing the decay of animal matter on the bottom of the extensive Devonian epicontinental seas. During the Carboniferous and yet more wholesale Permian and post-Permian emergence the fishes were driven out into deeper water, where they continued the gradual colonization of the entire sea floor. So far as the fishes are concerned that colonization may have been complete in Cretaceous time.‡ That, at any

* On account of the relatively small amount of time which could be occupied in compiling the data, the comparison of the limestones has been largely confined to the North American formations. A more qualitative study seems, however, to show that there has been a parallel succession of chemical types among the limestones of the other continents. One specially interesting parallel may be noted. The Great Dolomite of South Africa (part of the Potchefstroom series of the Transvaal) reaches a maximum thickness of 5,000 feet and covers very large areas. It is unfossiliferous, but is known to be of pre-Devonian age. In chemical composition, grain, structure, and great thickness this huge (marine) deposit seems to be very similar to the Siyeh limestone. The weathered outcrop has characteristically a 'curiously wrinkled or corrugated surface, resembling an elephant's skin'; hence the Dutch settlers have named the limestone 'Olifantsklip' (elephant rock). This corrugation is due to the more rapid solution of the calcareous parts of the rock as compared with the more magnesian parts, and is thus comparable to the roughening of the weathering surface of the Siyeh molar-tooth limestone. The average content of magnesia in the whole South African formation seems to be of the same order as that in the average pre-Devonian limestone of North America. See the 'Geology of South Africa' by F. H. Hatch and G. S. Corstorphine, London, 1905, p. 311.

† Cf. C. R. Van Hise. Treatise on Metamorphism, 1904, p. 801, and Chamberlin and Salisbury, Geology, Vol. 1, 1904, pp. 360, 404.

‡ This speculation regarding the migration of the fishes into bathybial and abyssal depths is confessedly little better than a guess, but it is stated partly to render the hypothesis somewhat more concrete and therefore more intelligible. Meagre as are the relevant facts concerning the fishes, those bearing on the Paleozoic and Mesozoic history of the bathybial and abyssal crustaceans, echinoderms, worms, and other scavenging species are almost nil. The profound mystery covering this subject does not, however, affect the general hypothesis favouring a nearly limeless ocean in pre-Cambrian time; for it is next to certain that the more efficient scavengers of the sea floor, being all relatively high types, were not abundantly developed in Cambrian and pre-Cambrian time.

rate, it was complete probably several million years ago seems evident from the chemistry of the present ocean. According to Murray, the calcium sulphate now dissolved in the ocean could be introduced by existing rivers in about 600,000 years. Since the sulphate is being rapidly decomposed by lime-secreting organisms and converted into deposited carbonate, it is probable that much more than 600,000 years have elapsed since the bathybial fishes and other scavengers colonized the general sea floor to depths of 2,500 fathoms. The test case of the Black sea shows that the present content of calcium sulphate in ocean water would be largely and rapidly diminished if the scavenging system were not now at work in the ocean.

The ratio of calcium to magnesium in the Ottawa river, the best available type of rivers draining the average pre-Cambrian terrane, is 3.69 : 1. The ratio for the Saint Lawrence, which is not far from representing a type of the rivers which might drain the average late Paleozoic terrane, is 4.44 : 1. The ratio for the Mississippi at Memphis, similarly a fair type of river draining the average terranes of the Triassic, Jurassic, or Cretaceous, is 2.50 : 1. The ratio for the Mississippi at New Orleans, a chemical world type for the present time is 3.92 : 1. The ratio for forty-four existing rivers is 4.18 : 1.* It appears, therefore, highly probable that the ratio of calcium to magnesium for the world's entire river system has been fairly constant from the pre-Cambrian to the present. We have seen that this ratio is almost identical with that in the average pre-Devonian limestone, but is much lower than the ratio for the Devonian and post-Devonian limestones. Granting that the calcium and magnesium in sea water have been introduced by the rivers, the sudden increase of the ratio Ca : Mg in the Devonian limestones must mean that during the Devonian the magnesium began to accumulate in the oceanic solution with special and unprecedented rapidity. On the hypothesis that the ocean was nearly limeless in pre-Cambrian time and very low in lime during early Paleozoic time, it follows that only a minute amount of magnesium could have remained in the oceanic solution during pre-Devonian time.

Since the period of the general colonization of the sea-floor, the precipitation of magnesium carbonate direct from sea water has been possible only under special conditions, so that the more recent times have seen minimum formation of magnesian deposits. The observations of Murray and Irvine on mud-waters suggest that, at the present day, there may be a slow addition of magnesium carbonate to the deposits of pure calcium carbonate shells or skeletons. A fairly pure calcareous ooze or shell-bank or a porous coral reef may be charged with decaying animal matter. Within the myriad interstices of the deposit there is sea water into which ammonium carbonate is being passed. This alkali precipitates all the calcium salts in the quasi-imprisoned water. Thereafter will follow a slow but steady precipitation of magnesium carbonate within the ooze

* So far as this ratio is concerned, a single analysis of a river may have high value in the discussion, since Dubois has shown that, no matter how much the absolute amounts of solute in a river may vary throughout the year, the proportions of the different salts remain nearly unchanged (E. Dubois, op. cit., p. 48).

or sand; if the amount of alkaline carbonate suffices, the magnesium salt may be added to the deposit in large amounts.

Whatever may be the exact chemistry of the process (perhaps mass-action in control) dolomitization of recently deposited calcareous matter does take place beneath the sea floor. The detailed studies of the boring at the Funafuti atoll have proved that fact beyond peradventure.* From the accounts of the different writers of the Funafuti report one must conclude that the extensive dolomitization in this case has been facilitated by the porous nature of the coral growth and coral-shell débris; the porosity permitting of the circulation of sea water. The impalpable, inorganic calcareous muds of the pre-Cambrian would evidently not be porous. It seems, therefore, probable that the dolomitization took place at the surface of the pre-Cambrian calcareous mud, the conditions there favouring the formation of the double salt at or very near the contact of mud and main water body. To-day the same chemical conditions seem to be found in the oceanic areas only at some depth below the surface of coral reef or of calcareous sands of direct organic origin.

There are yet other ways in which magnesium carbonate may be elaborated from sea-water—through certain algæ and a few animals known to secrete magnesium carbonate along with the dominant calcium carbonate of their hard structures, or, finally, through the local evaporation of sea water. However, the quantitative value of all these sources just mentioned may well be suspected to be but subsidiary to a more general cause of dolomite formation. Most of the world's magnesian limestones and dolomites seem to owe their origin neither to the secretions of special organisms nor to evaporation. The special organisms are too rare in one case; evaporation must be too local for the other case.

The scope of the present report does not permit of a critical discussion of the many published theories concerning the dolomites. It may only be stated that, if we accept the leaching hypothesis or the hypothesis that dolomite is the result of metamorphic processes by which magnesium comes to replace calcium in ordinary limestone, we meet with very grave difficulties, long ago stated and never overcome. The rapid alternation of clean-cut beds of pure or nearly pure calcium carbonate with other clean-cut beds of magnesian limestone or dolomite is a fact hardly to be reconciled with these metamorphic theories. The metamorphism is, by these theories, accomplished through the activities of circulating underground waters; yet it seems impossible that such wholesale metamorphism could leave the original bedding so well marked. The alternation of clean-cut beds as described is a prominent fact illustrated, for example, in the pre-Cambrian formations of Montana and British Columbia. The facts of the field speak rather for an original deposition of the two carbonates arranged in very nearly their present relations.

It is scarcely necessary to dwell on the effect of burial on the chemical precipitate of basic magnesium carbonate. Pressure and a heightened temperature have gradually driven out the water of crystallization. The simultaneous formation of the double carbonate, dolomite, might be expected where both carbonates

* The Atoll of Funafuti. Published by the Royal Society of London, 1904.

are present in large amount. The shrinkage consequent on the loss of water of crystallization amply accounts for the cavernous structure often seen in dolomites.

In conclusion, it appears that the hypothesis here proposed bears its third principal test so far as the carbonates of calcium and magnesium are concerned. It involves the precipitation of both carbonates from sea water through the decay of animal matter. The magnesium carbonate should have been most abundantly thrown down in pre-Cambrian time; its precipitation must have been lessened through Paleozoic and Mesozoic time, and has reached its minimum since the abysses of the ocean became abundantly tenanted with scavengers.

Origin of Certain Iron Ores, Cherts, and Jaspers.—In the preliminary paper a brief statement was given as to the possible origin of the lake Superior iron ores, cherts, and jaspers through precipitation from sea water by ammonium carbonate derived from decaying animal matter (American Journal of Science, Feb., 1907, pp. 110-111). These subjects are not directly relevant in the present connection and their discussion will not be attempted. Nevertheless, it may be noted that the regular association of dolomite with the ores, jaspers, etc., tends to corroborate the proposed hypothesis for the dolomites.

Origin of the Petroleum and Natural Gas Emanating from Pre-Cambrian Sediments.—Finally, the hypothesis of an almost limeless sea during Eozoic times correlates well with the undoubted fact that natural gas and petroleum are to-day issuing from pre-Cambrian strata. An excellent example of this is seen in the field now being prospected in the Flathead valley of British Columbia, at points situated far inside the eastern limit of the Rocky Mountains. The entombment of the carcasses of soft-bodied animals is, it is true, partly prevented by their bacterial decomposition, but doubtless not more so than by the steady removal of carcasses from the sea bottom by scavengers. Murray has shown that there is, in the deep-sea deposits of the present time, a considerable percentage of organic (soft-bodied) matter. This fact is all the more striking since there is evidence that the bottom muds are being worked over and over by scavengers through whose bodies pass inorganic and organic matter together. Before the general scavenging system for the sea floor was introduced we should expect a still higher proportion of such organic matter to enter into the composition of marine sediments. It is therefore not a matter of surprise that sufficient organic (soft-bodied) matter was entrapped within Eozoic sediment to furnish, after subsequent distillation, the oil and gas actually seen issuing from these old rocks. The greatest amount of entombment would be expected after the marine animals had begun to cover themselves with shells and skeletons (these structures retarding complete bacterial decay), and before the scavenging system was well established; it may be partly for this reason that the older Paleozoic formations are relatively so rich in petroleum and natural gas. Nevertheless, these fluids may emanate from rocks in which there is not a trace of shell or skeleton—rocks as unfossiliferous as so many pre-Cambrian formations.

DIRECT EVIDENCE OF THE CHEMICAL PRECIPITATION OF THE CARBONATE ROCKS IN THE PRIEST RIVER AND BELT-CAMBRIAN TERRANES.

Finally, we may turn to more direct evidences that the vast pre-Silurian limestone and dolomite deposits encountered in the Boundary belt, were originally chemical precipitates on the sea floor. This conclusion has been stated at several points in the detailed description of the Waterton, Altyn, Siyeh, Sheppard, and Creston (Eastern phase) formations, and it is only necessary to summarize the facts.

One of the leading arguments is the argument by exclusion. Some fourteen thin sections of typical phases of these formations have been specially studied under the microscope. The specimens were taken at localities ranging from Waterton lake to the Yahk river, a distance of 120 miles, and at horizons ranging through 12,000 feet of the Lewis series and through about as great a thickness in the Purcell series. In spite of such highly varied positions in the sedimentary prism, the grain of the carbonate rocks, as shown in the thin section and as implied in the never-varying compactness of the rock in the field, is most extraordinarily uniform.

The constituent grains are either idiomorphic and rhombohedral or anhedral and faintly interlocking. The former are everywhere of nearly constant average diameter, ranging from 0·01 to 0·03 mm., with an average of 0·02 mm. The anhedral grains range from 0·005 mm. or less to 0·03 mm., averaging about 0·015 mm.

This fineness and uniformity of grain persists not only in the compact Siyeh and Sheppard beds but also throughout the many beds of the Altyn, where coarse quartz and feldspar sands and pebbles are abundantly distributed in the carbonate base. Neither horizon nor distance from the old shore-line sensibly affects the singularly monotonous grain. In view of these facts regarding the the grain, in view of the rhombohedral forms of the one class of granules, and in view of the fact that there is no known pre-Belt carbonate formation at all adequate to furnish the materials for these tens of thousands of cubic miles of magnesian limestones, it seems impossible to credit them with a clastic origin. On the other hand, all the above-mentioned facts and the character of the bedding, which is often paper-thin and clean-cut as befits a precipitate, point directly to a chemical origin.

The argument is further strengthened by the fact that the much older Priest River dolomites seem to have had nearly the same grain and other general characteristics of the limestones in the overlying prism.

Secondly, it is important to note that the average diameters of the carbonate granules are of the same order as the average diameters of calcite and dolomite crystals which are unquestionably due to chemical precipitation from sea water or saline solutions at ordinary temperatures. Cullis has shown that the calcite granules deposited from sea water in the cavities of the Funafuti corals have average diameters of from 0·02 mm. to 0·03 mm.; also that the dolomite crystals which have gradually replaced the aragonite and calcite of the coral deposits, are of similar size.* When solutions of calcium chloride and alkaline (sodium) carbonate react at ordinary temperatures, crystals of calcium carbonate are slowly formed, which reach the same dimensions.† The granules constituting the 'eggs' of the Belt-Cambrian oolites likewise average 0·01 mm. to 0·02 mm. in diameter; the eggs are clearly chemical, inorganic growths.

In the few places where the Belt-Cambrian carbonate rocks at the Forty-ninth Parallel were observed to have been dynamically metamorphosed, the grain is coarsened.‡ Elsewhere and in general it is reasonable to suppose that we have the original grain more or less perfectly preserved.

Granting a chemical origin for these carbonate rocks, the genetic problem may be still further narrowed down by excluding the hypothesis of deposition within closed basins or lagoons. The scale of operations was altogether too vast to permit of our crediting the dolomites to the evaporation of sea water. Against that view is, further, the fact that there is no representative of the other inevitably expected evaporation deposits, like rock-salt, associated with the dolomites.

The hypothesis that the precipitation here occurred through organic decay on the open-sea floor is supported by the discovery of appreciable amounts of carbonaceous matter still resident in the Siyeh and other old limestones in the Boundary section.

But the choice between the various chemical hypotheses for the Belt-Cambrian and Priest River limestones and dolomites is to be made not simply on the basis of facts wholly derived from their study, but rather by the correlation of those facts with the great body of geological principles. The more those principles are developed the more clear is it becoming that strict uniformitarianism may err as vitally as the older doctrine of catastrophism. The pre-Silurian carbonate rocks at the Forty-ninth Parallel are entirely different physical and chemical types from the staple modern limestone. It seems, therefore, wrong to confine explanation only to limestone-forming processes now at work. Large-scale geological conditions and processes have had their evolution since Azoic times as surely as plants and animals have been evolved.

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* C. G. Cullis, The Atoll of Funafuti, London, 1904, p. 392; see text, figures and Plate F.

† H. B. Stocks, Quart. Jour. Geol. Soc., Vol. 58, 1902, p. 54.

‡ In his study of Norwegian marbles, Vogt has found that the rock of finest grain was made up of granules averaging 0.02 to 0·03 mm. in diameter. The grain varies directly with the intensity of the regional metamorphism suffered by the limestones and dolomites. He divides the marbles into seven classes on this basis, the coarsest marble showing average grains over 5 mm. in diameter. Vogt further states that these dolomitic interbeds are masses which were chemically deposited on the sea floor. From their association with conglomerates and quartzites he notes the implication that these dolomites and limestones are shallow-water deposits. The Norwegian field evidently offers a genetic problem which is similar to that attaching to the Forty-ninth Parallel section. It is therefore, gratifying to the present writer to find his conclusions so closely parallel to those of Vogt, whose paper was not discovered in the literature until this chapter was practically completed. See J. H. L. Vogt, Zeitschrift für Praktische Geologie, Jan. and Feb., 1898.

SUMMARY.

Premises.—The conclusions emphasized in this chapter are based on the following premises:—

1. The truth of the evolutionary hypothesis, especially as regards the geologically late development of active hunters and scavengers on the general sea floor;

2. The biologically deduced fact that the evolution of the main animal types, including those secreting hard parts, was accomplished in the ocean;

3. The fact that animal types were already highly diversified in Cambrian time;

4. The experimentally proved fact that representatives of the main animal types can live and thrive in sea water quite deprived of calcium salts;

5. The postulate that bacterial decomposition of animal remains occurred in Eozoic time and has occurred in all subsequent time;

6. The experimentally proved fact that bacterial decomposition of animal remains causes the emanation of ammonium carbonate among other products;

7. The experimentally proved fact that such ammonium carbonate can precipitate from sea water all of its calcium salts in the form of the carbonate and some of the magnesium salts as basic magnesium carbonate. (This precipitation is proved to be actually progressing on the floor of the Black Sea);

8. The experimentally proved fact that the precipitation of magnesium carbonate is facilitated by the absence or low content of calcium salts dissolved in sea water;

9. The probable fact that, in post-Middle Huronian (pre-Animikie) time, the land areas and therefore the river systems were greatly increased in size as a result of an orogenic revolution throughout the earth; much limestone then first exposed to weathering;

10. The fact that a prolonged period of partial or complete baselevelling followed the mountain-building period, implying a specially great addition of dissolved, river-borne calcium and magnesium salts to the ocean water. This addition of calcium salts is assumed to have made a fundamental change in the conditions of marine life; the excess of calcium salts being so great as to permit of the secretion of calcareous shells and skeletons for the first time;

11. The fact that the land areas have ever since retained sufficient size and abundance of limestone to furnish the sea with lime salts in excess of the amount of those salts being precipitated by ammonium carbonate and being deposited in the form of organic shells and skeletons on the sea floor.

12. The postulate that the chemical nature of the Ottawa, St. Lawrence, Mississippi, Danube, Rhone, Seine, and other rivers can give a tolerable idea of the necessary and drastic changes in calcium-content which must have characterized the world's river-system as it existed in pre-Cambrian, Paleozoic Mesozoic, and Tertiary times; a comparison of these rivers also showing the relative constancy of the ratio, Ca:Mg, in the average river-waters from the pre-Cambrian to the present time.

Conclusions.—1. The lime salts of the ocean, inherited from Azoic times, were precipitated as calcium carbonate comparatively soon after the introduction of animal life into the sea.

2. During most of Eozoic time, i.e., pre-Cambrian time in which animal life existed, the ocean was so nearly limeless that calcareous secretions by animals were impossible.

3. Tests and skeletons of pure chitin were possible in Eozoic time, but were not abundantly preserved until some carbonate or phosphate of lime was built into those structures. The calcareo-chitinous tests of Cambrian and Ordovician trilobites and shells of brachiopods represent a transition stage between the Eozoic æon of dominantly soft-bodied animals and the post-Cambrian æon of dominantly lime-secreting animals. The notable fossilization of brachiopods, trilobites, molluscs, etc., was impossible until near the beginning of Cambrian time. Indeed, the conditions for truly abundant fossilization of calcareous forms were not established until after the Cambrian period. The striking rarity or entire lack of organic remains in thick Cambrian sediments of British Columbia, Alberta, Idaho, and Montana, and in many other parts of the world, may be thus explained.

4. Eozoic limestones, dolomites, magnesian limestones, and calcareous and magnesian deposits generally were chemically deposited through the medium of organic ammonium carbonate. This alkali acted on the primeval calcium and magnesium salts (of the ocean and on the calcium and magnesium salts) introduced to the ocean by pre-Cambrian rivers. A similar origin is suggested for the iron carbonate occurring in Eozoic sedimentary beds. It is also suggested that possibly the silica of the cherts and jaspers characteristically associated with these carbonates, were likewise thrown out of solution by ammonium carbonate of organic origin. The petroleum and natural gas emanations from Eozoic sedimentary rocks receive explanation if the fundamental postulate of abundant Eozoic marine life be accepted.

5. The hypothesis seems to explain the greater development of magnesian rocks in the earlier geological formations, especially those belonging to the Eozoic æon. The hypothesis throws light on the formation of dolomitic rocks of all ages.

6. The ratio of calcium to magnesium is nearly constant in the average limestone of the pre-Cambrian, Cambrian, Ordovician, and Silurian terranes. The ratio increases abruptly in the Devonian limestones, possibly because of the rapid development of the fishes, which then began the more thorough scavenging of the sea floor.

7. The colonization of the sea floor, at least to the depths where calcium carbonate is not redissolved by pressure, was probably fairly complete in the Cretaceous period.

8. Magnesium salts first began to be accumulated in the ocean water probably during the early Devonian period.

9. It is suggested from the facts noted in this chapter that the magnesium now contained in the sea in amount greater than a mere trace began to accumu-

late not earlier than the Devonian period. The calcium did not begin to accumulate in similar excess until the general scavenging system was established in the 'bathybial' (not 'abyssal') regions of the ocean floor—perhaps as late as the Cretaceous period. When we also bear in mind that the sodium and potassium salts have been slowly accumulating from the pre-Cambrian to the present time, we are prepared to reach the rather probable conclusion that the pre-Cambrian ocean really approximated a *fresh-water* (though faintly acid) *condition.* The only escape from that conclusion seems to be offered in the view that a large part of the existing ocean is made of nearly pure 'juvenile' water emitted from volcanic vents or from primary igneous rocks since the pre-Cambrian.

10. The hypothesis suggests that, in general, secular variations in the oceanic composition may be found to explain some features of biological history, including certain accelerations and retardations in life development, especially as regards the elaboration of the hard parts of animals and the rise and fall of lime-secreting organisms.

11. According to the hypothesis the outlines of developments may be tabulated as follows:—

Life.	Oceanic Composition.	River influence on Oceanic Composition.	Carbonate Deposits.
	Azoic Period.		
	?	?	?
	Early Eozoic Period.		
Pelagic, soft-bodied, low types of animals and plants. Gradual evolution of higher types of animals, all soft-bodied. *Chief Fossils* — Silicious; impressions of soft-bodied animals; possibly tests of pure chitin; plants ?	Beginning of precipitation of lime-salts. Followed by a long, nearly limeless stage.	Minimum; land areas small; minimum area of limestone exposed to weathering	Calcium carbonate followed by mixed deposits of calcium carbonate and magnesium carbonate; iron carbonate.
	Late Eozoic (Post-Middle Huronian) Period.		
Relatively high types of animals, soft-bodied. *Chief Fossils* — As in former period; also, perhaps, some calcareo-chitinous.	Great and relatively rapid increase of river-borne carbonates of calcium and magnesium.	Orogenic revolution; land areas enlarged; special increase of areas of weathering limestones; base-levelling.	Relative abundance of calcium carbonate; continued deposit of magnesium and iron carbonate.

Life.	Oceanic Composition.	River influence on Oceanic Composition.	Carbonate Deposits.
TIME PLACE OF THE GREAT UNCONFORMITY.* *Cambrian Period.*			
Diversified animal types; beginning of lime secretion. *Chief Fossils.*—Calcareo-chitinous and calcareous.	Lime salts sufficient for lime secretion by animals.	Land areas probably diminished but still large in absolute measure.	Both chemically precipitated and directly organic calcium carbonate; magnesium carbonate in diminished proportion.
From Cambrian to Epoch of Colonization of General Sea floor.			
Limey structures of animals fully developed. *Chief Fossils.* — Calcareous.	Same as last period.	Land areas, and areas of weathering limestone, slowly though not steadily increasing.	Same as last period.
Period following Colonization of General Sea floor.			
Same as last period.	Gradual increase of calcium sulphate in solution.	Land areas approaching maximum extent. Rivers drain maximum area of limestone.	Directly organic calcium carbonate dominant; magnesium carbonate at its minimum.

* It may be noted that in British Columbia there is local conformity between the *Beltina* bed and the beds corresponding to the *Olenellus* zone. This is, of course, an exceptional relations between Cambrian and pre-Cambrian rocks as exposed on the continental plateaus.

CHAPTER XXIV.

INTRODUCTION TO THE THEORY OF IGNEOUS ROCKS.

Classification of the Igneous Rocks.

In this report the prevailing classification of igneous rocks, as compiled and elaborated by Rosenbusch, has been followed. Once again a prolonged study of large igneous areas has proved the value of his division of eruptives into three principal classes: the plutonic, the effusive, and the dike rocks. The distinction is obviously fundamental to the geologist, for he must never lose sight of the fact that the structural relations of igneous bodies indicate earth history as truly as do the series of stratified rocks with their contained fossils.

Likewise the petrologist, who is primarily interested in the origin of rocks and in the processes by which they have assumed their known compositions and structures, should regard this time-honoured, threefold division as essential. The general contrasts of texture and structure among the three classes are too patent to need emphasis. A fact less conspicuous but certainly worthy of distinct recognition in arranging a classification, is illustrated in the following table of chemical averages. It is there seen that the leading effusive types are steadily contrasted in a chemical way with the corresponding plutonics. The former are slightly but distinctly richer in silica and alkalies, and poorer in iron oxides, magnesia, and lime than the respective plutonic rocks. This relation is not fortuitous but is almost certainly a result of some kind of magmatic differentiation. A classification which obscures such principal indications of origin must be ranked as imperfect.

Most of the 'diaschistic' dike rocks have no direct equivalents among the plutonics or the effusives, and these chemical units are found nowhere else than in dikes or, more rarely, in sheets or other small injected bodies. True it is that the 'aschistic' dikes are essentially like corresponding plutonic rocks in chemical composition, but the petrogenist must give much more weight to the diaschistic division. Understood in this way, Rosenbusch's separation of the dike rocks from the other two classes seems to be a prime necessity to the investigator in the genesis of rocks.

Rosenbusch's principles of subdivision in each of the three great classes fulfil the requirements of the field geologist. A quantitative estimate of the actual mineralogical composition checked, ideally, by microscopic and chemical analysis, is the only natural basis of classification for the man in the field. According to the mode in which the minerals of rocks are assembled we have, thus, what has been called a Mode classification. Variable as igneous rocks may be, their modes represent a quite limited number of types, each of which becomes to the trained geologist as characteristic as the features of Caucasian or Mongolian are to the ethnographer. Rock, like man, has a 'habit' of its own and this is of first aid to the geologist who is mapping an igneous region.

A Mode classification seems also vital to the investigator in petrogeny. If rock magmas be only moderately superheated—the usual condition in nature—the dissociation of the molecules, which on cooling will form homogeneous crystals, is probably very slight. The actual minerals seen in a crystalline rock are, therefore, so many direct indications of the nature of the magma before it crystallized. Since it is becoming more and more certain that the laws of solution govern the phenomena of rock crystallization, it is legitimate, with proper safeguards, to reason from a rock's actual mineralogical constitution or 'mode,' to the condition of the pre-existing magma. The origin and history of magma is really the core of petrogeny. The professed petrogenist, no less than the field geologist, should regard the Mode classification as fundamental and, in a sense, final.

A further reason for its retention is found in the fact that a sound petrogeny must be based on an inductive study of the actual igneous terranes of the world. This study is now only possible through the maps and memoirs which, with a very few exceptions, have been composed in terms of the prevailing classification. Inasmuch as the field geologist must map areas according to the visible, mineralogical character of the rocks, the raw material for the comparative petrologist must retain essentially the same character as it has now. It is of the highest importance that the quantities (species) dealt with by geologist and petrogenist should have a common denominator. Where the two part company there is new opportunity for unsound hypotheses concerning the origin of the rocks in nature.

These are some of the reasons why the Norm classification of igneous rocks seems bound to be a failure for petrogenist and geologist alike. Harker's destructive criticism in the last chapter of his 'Natural History of Igneous Rocks' (1909) is hardly to be refuted. The nature of the highly artificial system is doubtless familiar to the reader of the present report and need not be described. While realizing the inefficacy of the system as a direct aid in the problems of rock genesis, it has this residual advantage that the norm calculated from a rock analysis may be used as a guide to the nearest chemical equivalents of that rock among modern types. For the purpose Washington's large compilation of analyses, for which the norms, subrangs, etc., have been determined, is of great service.* Largely for this reason the norms of the analyzed types occurring in the Boundary belt have been calculated.

There is no apparent reason why the Mode classification of the holocrystalline rocks should not be made rather strictly quantitative, somewhat after the manner of calculation by which the position of a rock is found in the Norm system. Thanks to Rosiwal's well-known method the modes can be calculated for most of these rocks. In a measure the same is true for porphyritic rocks with aphanitic

* H. S. Washington, 'Chemical Analyses of Igneous Rocks published from 1884 to 1900,' Professional Paper, No. 14, U.S. Geol. Survey, 1903.

or glassy base. Since the holocrystalline rocks are overwhelmingly preponderant, and since nearly all of the glassy and ultra-compact rocks are chemical equivalents of respective holocrystalline types, it seems possible to make an essentially complete and highly useful Mode classification of igneous rocks on a quantitative basis. The existing Mode classification is only sub-quantitative and, in the writer's opinion, would be strengthened by closer precision in its definitions. A tentative experiment has shown that Rosenbusch's plutonic types can be usefully defined in terms of limits in the quantities of the essential minerals, and that without causing any marked changes in the names which Rosenbusch has adopted. Leaving further demand to decide the advisability of such a restating of the Mode classification, we may note the quantitative basis of the present system as shown in the average chemical analyses of the now recognized types.

Average Compositions of Leading Types.

These averages have been calculated by the writer according to the method described in a special paper, which also hints at some of the uses to which the averages may be put.* More surely than single averages they illustrate the essential chemical nature of the world types as actually encountered in the field. The individuality and objective character of the types are as well shown as in the mineralogical composition of the corresponding rocks. The averages are here entered in the succeeding table (XLIV), in order to facilitate comparison with the many analyses made from the Boundary Survey collection.

In summary, the writer may state as his reasons for using the Mode classification, not only that it is the prevailing one, nor simply because it is the best of the available systems for the field geologist, but also because it is a real approximation to the natural classification for geologist and petrogenist. It takes account of the actual mineral composition and of the chemical composition, each of which is a fairly direct expression of magma and of magmatic history. The Mode classification may be somewhat affected in form through the future application of entectic principles, but the leading types of igneous rocks as now usually recognized, will doubtless remain in the system.

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* R. A. Daly, Proceedings American Academy of Arts and Sciences, Vol. 45, 1910, p. 211.

TABLE XLIV.—*Showing the average compositions calculated for the Principal Igneous-rock Types.*

GROUP I.

	Plutonics.				Effusives.			
	1	2	3	4	5	6	7	8
	Pre-Cambrian Granites, including 16 analyses of Swedish types (Osann).	Pre-Cambrian Granites of Sweden (Holmquist).	Granites younger than the Pre-Cambrian (Osann and Clarke).	Granite of all periods (Osann and Clarke).	Liparite, including 40 Rhyolites (Osann).	Liparites, as named by authors (Osann).	Rhyolites, as named by authors (Osann).	Quartz Porphyry (Osann).
No. of Analyses.	47	114	184	236	64	24	40	50
SiO_2.....	71·06	69·81	69·73	69·92	72·60	72·90	72·62	72·36
TiO_2.....	·48	·54	·34	·39	·30	·48	·25	·33
Al_2O_3....	14·10	13·76	14·98	14·78	13·88	14·18	13·77	14·17
Fe_2O_3....	1·46	2·17	1·62	1·62	1·43	1·65	1·29	1·55
FeO.....	1·63	1·87	1·66	1·67	·82	·31	·90	1·01
MnO....	·18	·26	·11	·13	·12	·13	·12	·09
MgO....	·59	·84	1·08	·97	·38	·40	·38	·52
CaO.....	1·97[1]	2·20	2·20[2]	2·15[3]	1·32	1·13	1·43	1·38
Na_2O....	3·24	3·17	3·28	3·28	3·54	3·54	3·55	2·85
K_2O.....	4·50	4·38	3·95	4·07	4·03	3·94	4·09	4·56
H_2O.....	·69	·74	·78	·78	1·52	1·33	1·53	1·09
P_2O_5.....	·10	·26	·27	·24	·06	·01	·07	·09

CALCULATED AS WATER-FREE.

	1	2	3	4	5	6	7	8
SiO_2....	71·56	70·33	70·28	70·47	73·72	73·89	73·75	73·16
TiO_2.....	·48	·54	·34	·39	·30	·49	·25	·33
Al_2O_3....	14·20	13·86	15·10	14·90	14·10	14·37	13·99	14·33
Fe_2O_3....	1·47	2·19	1·63	1·63	1·45	1·67	1·31	1·57
FeO.....	1·65	1·89	1·67	1·68	·83	·31	·91	1·02
MnO....	·18	·26	·11	·13	·12	·13	·12	·09
MgO....	·59	·85	1·09	·98	·40	·41	·39	·53
CaO.....	1·98[1]	2·22	2·22[2]	2·17[3]	1·34	1·14	1·45	1·39
Na_2O....	3·26	3·19	3·31	3·31	3·59	3·59	3·60	2·88
K_2O.....	4·53	4·41	3·98	4·10	4·09	3·99	4·16	4·61
P_2O_5....	·10	·26	·27	·24	·06	·01	.07	·09

Each sum = 100·00. [1] Includes ·08% BaO and ·01% SrO. [2] Includes ·06% BaO and ·02% SrO. Includes ·06% BaO and ·02% SrO.

GROUP II.

	Plutonics.					Effusives		
	9	10	11	12	13	14	15	16
	Nordmarkite (Osann and Washington).	Pulaskite (Osann and Washington).	Akerite (Osann and Washington).	Average Alkaline Syenite, including 7 Nordmarkites, 5 Pulaskites, 9 Akerites, and 3 Laurvikites.	All Syenite, including five types of 'Alkaline Syenite.'	Trachyte (Osann and Rosenbusch).	Keratophyre (Osann and Washington).	Quartz Keratophyre (Rosenbusch).
No. of Analyses.	7	5	8	23	50	48	7	13
SiO_2	64.36	61·86	61·96	61·99	60·19	60·68	61·51	75·45
TiO_2	·45	·15	·99	·56	·67	·38	·45	·17
Al_2O_3	16·81	19·07	17·07	17·93	16·28	17·74	17·37	13·11
Fe_2O_3	1·08	2·65	2·35	2·22	2·74	2·64	1.92	1·14
FeO	2·71	1·49	3·37	2·29	3·28	2·62	3·35	·66
MnO	·15	·01	·09	·08	·14	·06	·01	·29
MgO	·72	·55	1·38	·96	2·49	1·12	1·26	·34
CaO	1·55	1·47	3·41	2·55	4·30	3·09	1·08	·83
Na_2O	5·76	6·45	4·65	5·54	3·98	4·43	5·23	5·88
K_2O	5·62	5·75	3·80	4·98	4·49	5·74	5·29	1·26
H_2O	·70	·47	·93	·76	1·16	1·26	2·45	·69
P_2O_5	·09	·08	....	·14	·28	·24	·08	·18

Calculated as Water-free.

	9	10	11	12	13	14	15	16
SiO_2	64·81	62·15	62·55	62·46	60·90	61·46	63·06	75·98
TiO_2	·45	·15	1·00	·56	·68	·38	·46	·17
Al_2O_3	16·93	19·16	17·23	18·07	16·47	17·97	17·81	13·20
Fe_2O_3	1·09	2·66	2·37	2·24	2·77	2·67	1·97	1·15
FeO	2·73	1·50	3·40	2·31	3·32	2·66	3·43	·66
MnO	·15	·01	·09	·08	·14	06	·01	·29
MgO	·73	·55	1·39	·97	2·52	1·13	1·29	·34
CaO	1·56	1·48	3·44	2·57	4·35	3·13	1·11	·84
Na_2O	5·80	6·48	4 69	5·58	4·03	4·49	5·36	5·92
K_2O	5·66	5·78	3·84	5·02	4·54	5·81	5·42	1·27
P_2O_5	·09	·08	....	·14	·28	·24	·08	·18

Each sum = 100·00.

GROUP III.

	Plutonic.	Effusive.	Plutonic.	Effusive.
	17	18	19	20
	Laurvikite (Osann).	Rhomb-porphyry (Washington).	Monzonite (Osann and Washington).	Latite (Ransome and Daly).
No. of Analyses.	3	7	12	10
SiO_2	57·45	57·45	55·25	57·65
TiO_2	.....	.....	·60	1·00
Al_2O_3	21·11	19·53	16·53	16·68
Fe_2O_3	2·89	6·47	3·03	2·29
FeO	2·39		4·37	4·07
MnO	.....	.....	·15	·10
MgO	1·06	1·28	4·20	3·22
CaO	4·10	3·11	7·19	5·74[1]
Na_2O	5·89	6·35	3·48	3·59
K_2O	3·87	4·46	4·11	4·39
H_2O	·70	1·35	·66	·91[2]
P_2O_5	·54	.....	·43	·36

Calculated as Water-free.

	17	18	19	20
SiO_2	57·85	58·24	55·62	58·18
TiO_2	.....	.....	·60	1·01
Al_2O_3	21·26	19·79	16·64	16·84
Fe_2O_3	2·91	6·56	3·05	2·31
FeO	2·41		4·40	4·11
MnO	.....	.....	·15	·10
MgO	1·07	1·30	4·23	3·25
CaO	4·13	3·15	7·24	5·79[1]
Na_2O	5·93	6·44	3·50	3·62
K_2O	3·90	4·52	4·14	4·43
P_2O_5	·54	.....	·43	·36

Each sum = 100·00. [1] Includes .16% BaO and .07% SrO. [2] Includes .14% CO_2.

GROUP IV.

	Plutonics.				Effusives.		
	21	22	23	24	25	26	27
	Foyaite (Osann and Rosenbusch).	Urtite (Osann).	Laurdalite (Osann).	Nephelite syenite (Osann).	Phonolite (Osann, Clarke, and Lacroix).	Leucite Phonolite (Osann and Washington).	Leucitophyre (Washington and Rosenbusch).
No. of Analyses.	10	3	3	43	25	4	8
SiO_2	56·11	45·61	54·36	54·63	57·45	54·89	49·83
TiO_2	·45	....	1·30	·86	·41	....	·71
Al_2O_3	21·33	27·76	19·99	19·89	20·60	21·28	19·00
Fe_2O_3	1·87	3·67	2·79	3·37	2·35	3·04	3·17
FeO	1·47	·50	2·58	2·20	1·03	1·49	3·59
MnO	·05	·15	·18	·35	·13	·01	·17
MgO	·55	·19	1·72	·87	·30	·66	1·79
CaO	1·72	1·73	2·96	2·51	1·50	2·31	5·69
Na_2O	8·48	16·25	8·28	8·26	8·84	5·62	7·19
K_2O	6·46	3·72	4·98	5·46	5·23	8·39	6·15
H_2O	1·50	·42	·22	1·35	2·04	2·31	1·93
P_2O_5	·01	....	·64	·25	·12	....	·78

Calculated as Water-free.

	21	22	23	24	25	26	27
SiO_2	56·96	45·80	54·48	55·38	58·65	56·19	50·82
TiO_2	·46	....	1·30	·87	·42	....	·72
Al_2O_3	21·65	27·88	20·03	20·16	21·03	21·78	19·38
Fe_2O_3	1·90	3·68	2·80	3·42	2·40	3·11	3·23
FeO	1·49	·50	2·59	2·23	1·05	1·53	3·66
MnO	·05	·15	·18	·35	·13	·01	·17
MgO	·56	·19	1·72	·88	·31	·68	1·83
CaO	1·75	1·74	2·97	2·54	1·53	2·36	5·80
Na_2O	8·61	16·32	8·30	8·38	9·02	5·75	7·33
K_2O	6·56	3·74	4·99	5·54	5·34	8·59	6·27
P_2O_5	·01	....	·64	·25	·12	....	·79

Each sum = 100·00.

GROUP V.

	Pl.	Ef.	Plutonics.			Effusives.				
	28	29	30	31	32	33	34	35	36	37
	Granodiorite (Osann and Clarke).	Dacite (Osann and Rosenbusch).	Quartz Diorite (Osann and Washington).	Diorite, including Quartz Diorite (Osann).	Diorite, excluding Quartz Diorite (Osann).	All Andesite (Osann).	Augite Andesite (Osann).	Hypersthene Andesite (Osann).	Hornblende (Amphibole) Andesite (Osann).	Mica Andesite (Osann).
No. of Analyses.	12	30	20	89	70	87	33	20	24	10
SiO_2	65·10	66·91	59·47	58·38	56·77	59·59	57·50	59·48	61·12	62·25
TiO_2	·54	·33	·64	·80	·84	·77	·79	·48	·42	1·65
Al_2O_3	15·82	16·62	16·52	16·28	16·67	17·31	17·33	17·38	17·65	16·10
Fe_2O_3	1·64	2·44	2·63	2·98	3·16	3·33	3·78	2·96	2·89	3·62
FeO	2·66	1·33	4·11	4·11	4·40	3·13	3·62	3·67	2·40	2·20
MnO	·05	·04	·08	·13	·13	·18	·22	·15	·15	·21
MgO	2·17	1·22	3·75	3·88	4·17	2·75	2·86	3·28	2·44	2·03
CaO	4·66	3·27	6·24	6·38	6·74	5·80	5·83	6·61	5·80	4·05
Na_2O	3·82	4·13	2·98	3·34	3·39	3·58	3·53	3·41	3·83	3·55
K_2O	2·29	2·50	1·93	2·09	2·12	2·04	2·36	1·64	1·72	2·44
H_2O	1·09	1·13	1·39	1·37	1·36	1·26	1·88	·74	1·43	1·50
P_2O_5	·16	·08	·26	·26	·25	·26	·30	·20	·15	·40

Calculated as Water-free.

SiO_2	65·82	67·67	60·31	59·19	57·56	60·35	58·65	59·92	62·01	63·20
TiO_2	·55	·33	·65	·81	·85	·78	·80	·48	·43	1·67
Al_2O_3	15·99	16·81	16·75	16·51	16·90	17·54	17·67	17·51	17·91	16·35
Fe_2O_3	1·66	2·47	2·67	3·02	3·20	3·37	3·85	2·98	2·93	3·67
FeO	2·69	1·35	4·17	4·17	4·46	3·17	3·69	3·70	2·44	2·23
MnO	·05	·04	·08	·13	·13	·18	·22	·15	·15	·21
MgO	2·19	1·23	3·80	3.93	4·23	2·78	2·90	3·31	2·48	2·06
CaO	4·71	3·31	6·33	6·47	6·83	5·87	5·92	6·66	5·88	4·11
Na_2O	3·86	4·18	3·02	3·39	3·44	3·63	3·60	3·44	3·88	3·61
K_2O	2·32	2·53	1·96	2·12	2·15	2·07	2·40	1·65	1·74	2·48
P_2O_5	·16	·08	·26	·26	·25	·26	·30	·20	·15	·41

Each sum = 100·00.

GROUP VI.

	Plutonics.		Effusives.					
	38	39	40	41	42	43	44	45
	All Norite (Osann and Walker).	All Gabbro (Osann).	All Basalt, including 161 Basalts, 17 Olivine Diabases, 11 Melaphyres, and 9 Dolerites (Osann).	Basalt, as named by Authors (including also Anamesite, Tachylite, &c.) (Osann).	Diabase (Osann).	Olivine Diabase (Osann).	Melaphyre (Osann).	Dolerite (Osann).
No. of Analyses.	7	41	198	161	20	17	11	9
SiO_2......	50·16	48·24	49·06	48 78	50·12	50·10	50·60	49·50
TiO_2.	1·64	·97	1·36	1·39	1·41	1·25	·68	1·42
Al_2O_3.....	18·51	17·88	15·70	15·85	15·68	14·43	17·40	14·37
Fe_2O_3	1·88	3·16	5·38	5·37	4·55	5·06	4·57	6·55
FeO.....	9·29	5·95	6·37	6·34	6·73	6·31	6·29	5·84
MnO.....	·14	·13	·31	·29	·23	·25	·46	·17
MgO.	5·97	7·51	6·17	6·03	5·85	7·32	4·89	7·75
CaO......	7·90	10·99	8·95	8·91	8·80	9·53	8·09	9·96
Na_2O.....	2·72	2·55	3·11	3·18	2·95	2·75	3·23	2·50
K_2O.......	·80	·89	1·52	1·63	1·38	·73	1·76	·84
H_2O..	·76	1·45	1·62	1·76	1·93	2·00	1·83	·66
P_2O_5......	·23	·28	·45	·47	·37	·27	·20	·44

Calculated as Water-free.

SiO_2..	50·54	48·95	49·87	49·65	51·11	51·12	51·54	49·83
TiO_2......	1·65	·98	1·38	1·41	1·44	1·27	·69	1·43
Al_2O_3.. ..	18·65	18·15	15·96	16·13	15·99	14·73	17·73	14·47
Fe_2O_3.....	1·90	3·21	5·47	5·47	4·64	5·16	4·66	6·59
FeO......	9·36	6·04	6·47	6·45	6·86	6·44	6·41	5·88
MnO.....	·14	·13	·32	·30	·23	·25	·47	·17
MgO.	6·02	7·62	6·27	6·14	5·96	7·47	4·99	7·80
CaO..	7·96	11·15	9·09	9·07	8·97	9·73	8·24	10·02
Na_2O.....	2·74	2·59	3·16	3·24	3·01	2·81	3·29	2·52
K_2O......	·81	·90	1·55	1·66	1·41	·74	1·78	·85
P_2O_5..	·23	·28	·46	·48	·38	·28	·20	·44

Each sum = 100.00.

GROUP VII.

	Plutonics.				
	46	47	48	49	50
	Gabbro, excluding Olivine Gabbro (Osann).	Olivine Gabbro (Osann).	Norite excluding Olivine Norite (Osann and Walker).	Olivine Norite (Osann).	Anorthosite (Osann and Washington).
No. of Analyses.	24	17	5	2	12
SiO_2	49·50	46·49	50·08	50·38	50·40
TiO_2	·84	1·17	1·44	2·04	·15
Al_2O_3	18·00	17·73	18·62	18·27	28·30
Fe_2O_3	2·80	3·66	2·35	·73	1·06
FeO	5·80	6·17	8·87	10·35	1·12
MnO	·12	·17	·11	·20	·05
MgO	6·62	8·86	6·22	5·32	1·25
CaO	10·64	11·48	7·89	7·91	12·46
Na_2O	2·82	2·16	2·53	3·18	3·67
K_2O	·98	·78	·71	1·02	·74
H_2O	1·60	1·04	1·01	·26	·75
P_2O_5	·28	·29	·17	·34	·05

Calculated as Water-free.

	46	47	48	49	50
SiO_2	50·31	46·97	50·60	50·51	50·78
TiO_2	·85	1·18	1·45	2·05	·15
Al_2O_3	18·30	17·92	18·81	18·32	28·51
Fe_2O_3	2·85	3·70	2·37	·73	1·07
FeO	5·89	6·24	8·96	10·38	1·13
MnO	·12	·17	·11	·20	·05
MgO	6·73	8·96	6·28	5·33	1·26
CaO	10·81	11·60	7·97	7·93	12·55
Na_2O	2·86	2·18	2·56	3·19	3·70
K_2O	1·00	·79	·72	1·02	·75
P_2O_5	·28	·29	·17	·34	·05

Each sum = 100·00.

GROUP VIII.

	Plutonics.							Effusive.
	51	52	53	54	55	56	57	58
	Lherzolite (Osann).	Websterite (Osann).	Wehrlite (Osann).	Harzburgite, including Saxonite (Osann and Washington).	Dunite (Washington)	Pyroxenite (Osann).	All Peridotite (Osann).	Picrite (Osann).
No. of Analyses.	4	4	3	4	3	4	49	3
SiO_2	42·09	53·65	48·13	43·85	40·06	49·82	44·39	43·24
TiO_2	·12	·14	·87	....	....	1·46	·88	....
Al_2O_3	4·83	1·66	6·50	5·00	·57	5·12	5·14	15·19
Fe_2O_3	4·98	1·90	2·01	2·54	2·29	1·83	3·88	8·62
FeO	4·58	5·35	11·73	6·30	7·32	7·44	6·70	7·89
MnO	·06	·17	·08	·12	·24	·09	·19	....
MgO	31·80	22·57	21·01	36·96	46·62	19·55	29·17	8·56
CaO	6·37	13·37	6·17	2·70	·35	13·00	6·31	13·78
Na_2O	1·02	·20	1·15	....	·01	·37	·64	·54
K_2O	·29	·07	·58	....	....	·21	·76	·48
H_2O	3·85	·85	1·62	2·53[1]	2·53	1·06	1·80	1·21
P_2O_5	·01	·07	·15	....	·01	·05	·14	·49

Calculated as Water-free.

	51	52	53	54	55	56	57	58
SiO_2	43·78	54·11	48·93	44·99	41·10	50·36	45·20	43·77
TiO_2	·12	·14	·88	....	....	1·48	·90	....
Al_2O_3	5·02	1·67	6·61	5·13	·58	5·17	5·25	15·37
Fe_2O_3	5·18	1·92	2·04	2·61	2·35	1·85	3·95	8·72
FeO	4·77	5·40	11·92	6·46	7·51	7·52	6·82	7·99
MnO	·06	·17	·08	·12	·25	·09	·19	....
MgO	33·08	22·76	21·36	37·92	47·83	19·76	29·70	8·66
CaO	6·62	13·49	6·27	2·77	·36	13·14	6·43	13·95
Na_2O	1·06	·20	1·17	....	·01	·37	·65	·55
K_2O	·30	·07	·59	....	....	·21	·77	·49
P_2O_5	·01	·07	·15	....	·01	·05	·14	·50

Each sum = 100·00. [1] Loss on ignition.

GROUP IX.

	Plutonic.	Effusives.		
	59	60	61	62
	Essexite (Osann and Rosenbusch).	Trachydolerite (Rosenbusch).	Limburgite (Zirkel).	Augitite (Osann, Washington, and Rosenbusch).
No. of Analyses.	11	4	7	6
SiO_2	48·40	54·81	41·69	42·25
TiO_2	1·71	·42	·67	2·52
Al_2O_3	16·67	20·01	14·80	16·26
Fe_2O_3	5·31	3·98	15·04	8·43
FeO	6·03	1·93		5·46
MnO	·15	....	....	....
MgO	4.48	2·32	8·64	5·49
CaO	9·05	5·60	11·98	9·75
Na_2O	4·45	5·86	3·52	4·45
K_2O	2·13	3·13	1·17	1·92
H_2O	·95	1·46	2·36	2·43
P_2O_5	·67	·48	·13	1·04

Calculated as Water-free.

	59	60	61	62
SiO_2	48·86	55·62	42·69	43·30
TiO_2	1·73	·43	·68	2·58
Al_2O_3	16·83	20·31	15·18	16·67
Fe_2O_3	5·36	4·04	15·43	8·64
FeO	6·09	1·96		5·59
MnO	·15	....	....	....
MgO	4·52	2·35	8·85	5·63
CaO	9·14	5·68	12·27	9·99
Na_2O	4·49	5·94	3·58	4·56
K_2O	2·15	3·18	1·19	1·97
P_2O_5	68	·49	·13	1·07

Each sum = 100·00.

GROUP X.

	Plutonics.		Effusives.					
	63	64	65	66	67	68	69	70
	Theralite (Osann).	Shonkinite (Pirsson).	All Tephrite.	All Basanite.	Nephelite Tephrite (Osann).	Leucite Tephrite (Osann and Washington).	Nephelite Basanite (Osann).	Leucite Basanite (Osann and Washington).
No. of Analyses.	6	6	24	20	4	20	16	4
SiO_2	45·61	48·66	49·14	44·41	46·91	49·90	44·20	45·34
TiO_2	1·96	·97	1·00	1·56	1·81	·16	1·64	1·30
Al_2O_3	14·35	12·36	16·57	15·81	15·25	16·94	15·64	16·59
Fe_2O_3	6·17	3·08	3·65	4·66	7·70	3·02	4·35	5·83
FeO	4·03	5·86	6·68	5·85	4·06	7·15	6·14	4·76
MnO	·19	·13	·30	·14	1·43	·23	·19	·01
MgO	6·05	8·09	3·98	8·20	2·95	4·22	8·89	5·43
CaO	9·49	10·46[1]	9·88	10·12	9·36	10·04	9·74	11·64
Na_2O	5·12	2·71	2·57	3·81	4·25	2·24	4·03	2·93
K_2O	3·69	5·15	3·39	2·37	2·63	3·57	1·83	4·55
H_2O	2·60	1·46	2·00	2·42	2·51	1·74	2·67	1·12
P_2O_5	·74	1·07	·84	·65	1·14	·79	·68	·50

Calculated as Water-free.

	63	64	65	66	67	68	69	70
SiO_2	46·83	49·38	50·15	45·51	48·12	50·79	45·41	45·86
TiO_2	1·98	·98	1·02	1·60	1·86	·16	1·68	1·31
Al_2O_3	14·73	12·55	16·90	16·20	15·65	17·24	16·07	16·78
Fe_2O_3	6·34	3·12	3·72	4·78	7·89	3·07	4·47	5·90
FeO	4·14	5·95	6·82	5·99	4·16	7·28	6·31	4·81
MnO	·19	·13	·31	·14	1·47	·23	·20	·01
MgO	6·22	8·21	4·06	8·41	3·02	4·30	9·13	5·49
CaO	9·75	10·62[2]	10·08	10·37	9·60	10·22	10·01	11·77
Na_2O	5·27	2·75	2·62	3·90	4·36	2·28	4·14	2·96
K_2O	3·79	5·23	3·46	2·43	2·70	3·63	1·88	4·60
P_2O_5	·76	1·08	·86	·67	1·17	·80	·70	·51

Each sum = 100·00. [1] Includes ·40% BaO and ·09% SrO. [2] Includes ·41% BaO and ·09% SrO.

GROUP XI.

	Plutonics.		Effusives.		Plutonic.	Effusives.	
	71	72	73	74	75	76	77
	Fergusite (Pirsson).	Missourite (Pirsson and Daly).	Leucite Basalt (Osann and Rosenbusch).	Leucitite (Osann and Rosenbusch).	Ijolite (Osann).	Nephelinite (Rosenbusch).	Nephelite Basalt (Osann).
No. of Analyses.	1	2	7	7	5	9	26
SiO_2	51·70	44·27	46·47	47·72	43·51	41·17	39·87
TiO_2	·23	1·37	1·33	·52	1·07	1·35	1·50
Al_2O_3	14·50	10·73	15·97	18·19	19·54	16·83	13·58
Fe_2O_3	5·07	3·63	5·97	4·74	3·77	7·61	6·71
FeO	3·58	5·87	4·27	3·90	3·88	6·64	6·43
MnO	·01	·06	·01	·06	·16	·16	·21
MgO	4·55	13·05	5·87	3·45	2·94	3·72	10·46
CaO	7·40[1]	11·46[2]	10·54	7·27	9·89	10·12	12·36
Na_2O	2·93	1·07	1·69	4·51	10·58	6·45	3·85
K_2O	7·60	4·43	4·83	7·66	2·26	2·49	1·87
H_2O	2·25	3·23	2·32	1·51	·86	2·42	2·22[3]
P_2O_5	·18	·83	·73	·47	1·54	1·04	·94

Calculated as Water-free.

	71	72	73	74	75	76	77
SiO_2	52·89	45·75	47·58	48·45	43·89	42·19	40·77
TiO_2	·24	1·41	1·36	·53	1·08	1·38	1·53
Al_2O_3	14·83	11·09	16·35	18·47	19·71	17·25	13·88
Fe_2O_3	5·18	3·75	6·11	4·81	3·80	7·79	6·86
FeO	3·66	6·07	4·37	3·96	3·91	6·81	6·57
MnO	·01	·06	·01	·06	·16	·17	·21
MgO	4·65	13·49	6·01	3·50	2·97	3·81	10·73
CaO	7·57[4]	11·85[5]	10·79	7·38	9·98	10·37	12·65
Na_2O	3·00	1·10	1·73	4·58	10·67	6·61	3·94
K_2O	7·79	4·57	4·94	7·78	2·28	2·55	1·90
P_2O_5	·18	·86	·75	·48	1·55	1·07	·96

Each sum = 100·00. [1] Includes ·30% BaO and ·07% SrO.
[2] Includes ·48% BaO and ·18% SrO. [3] Includes ·29% CO_2.
[4] Includes ·31% BaO and ·07% SrO. [5] Includes ·50% BaO and ·19% SrO.

GROUP XII.

	Plutonics.		
	78	79	80
	Alaskite (Osann).	Diorite of Electric Peak (Rosenbusch).	Malignite (Osann and Daly).
No. of Analyses.	3	10	4
SiO_2	76·47	62·21	50.34
TiO_2	·07	·60	·34
Al_2O_3	13·03	16·45	14·75
Fe_2O_3	1·04	2·53	4·18
FeO		2·89	2·75
MnO	·01	·02	·11
MgO	·06	3·32	4·23
CaO	·45	4·96	10·43
Na_2O	3·53	3·88[1]	5·27
K_2O	4·81	2·21	5·21
H_2O	·52	·80[2]	1·20
P_2O_5	·01	·13	1·19

Calculated as Water-free.

SiO_2	76·87	62·71	50·95
TiO_2	·07	·60	·35
Al_2O_3	13·10	16·58	14·93
Fe_2O_3	1·05	2·55	4·23
FeO		2·92	2·78
MnO	·01	·02	·11
MgO	·06	3·35	4·28
CaO	·45	5·00	10·56
Na_2O	3·55	3·91[1]	5·33
K_2O	4·83	2·23	5·27
P_2O_5	·01	·13	1·21

Each sum = 100·00. [1] Includes ·07% Li_2O. [2] Includes ·05% Cl and ·05% SO_3.

GROUP XIII.

	Effusives.						
	81	82	83	84	85	86	87
	Rhyolite of Yellowstone Park (Iddings)	Basalt of Hawaii (Osann).	Banakite (Osann).	Shoshonite (Osann).	Absarokite (Osann).	Leucite Absarokite (Osann).	Melilite Basalt (Osann).
No. of Analyses.	10	11	4	8	5	2	6
SiO_2	74·04	48·36	52·04	53·56	50·11	47·45	36·19
TiO_2	·18	·66	·76	·82	·96	·81	7·11
Al_2O_3	13·19	15·40	17·65	17·88	13·04	11·43	10·52
Fe_2O_3	1·35	6·48	4·66	4·51	4·58	3·22	8·48[1]
FeO	1·01	10·07	2·75	3·05	3·94	5·78	5·97
MnO	·04	·80	·13	·07	·11	·12	....
MgO	·32	4·19	3·33	3·62	9·27	14·60	14·59
CaO	1·19	8·69	5·11	6·45	7·63	8·18	9·88
Na_2O	3·88	3·34	4·10	3·41	1·94	2·32	3·28
K_2O	3·75	1·30	5·03	3·76	4·15	2·99	2·03
H_2O	1·02[2]	·43	3·74	2·32	3·58	2·50	1·94[3]
P_2O_5	·03	·28	·70	·55	·69	·60	·01

Calculated as Water-free.

	81	82	83	84	85	86	87
SiO_2	74·80	48·57	54·06	54·84	51·97	48·67	36·90
TiO_2	·18	·66	·79	·84	1·00	·83	7·25
Al_2O_3	13·33	15·47	18·34	18·31	13·52	11·73	10·73
Fe_2O_3	1·37	6·51	4·84	4·62	4·74	3·30	8·65[4]
FeO	1·02	10·11	2·85	3·12	4·08	5·93	6·09
MnO	·04	·80	·14	·07	·12	·12	....
MgO	·32	4·21	3·46	3·70	9·62	14·97	14·88
CaO	1·20	8·73	5·31	6·60	7·91	8·39	10·08
Na_2O	3·92	3·35	4·26	3·49	2·01	2·38	3·34
K_2O	3·79	1·31	5·22	3·85	4·31	3·06	2·07
P_2O_5	·03	·28	·73	·56	·72	·62	·01

Each sum = 100·00. [1] Includes 2·85% Cr_2O_3. [2] Includes ·02% Li_2O and ·23% SO_3. [3] Loss on ignition. [4] Includes 2·47% Cr_2O_3.

GROUP XIV.

	Dike-rocks.				
	88	89	90	91	92
	Granite-aplite (Osann and Washington).	Bostonite (Rosenbusch and Washington).	Grorudite (Osann and Washington).	Sölvsbergite (Osann and Washington).	Tinguaite (Osann and Washington).
No. of Analyses.	15	5	5	8	15
SiO_2	75·00	61·32	70·91	62·16	55·02
TiO_2	·30	·89	·48	·31	·36
Al_2O_3	13·14	18·43	11·50	17·58	20·42
Fe_2O_3	·58	3·84	4·58	3·05	3·06
FeO	·40	1·60	1·88	1·80	1·82
MnO	·07	·01	·39	·18	·22
MgO	·30	·46	·11	·48	·59
CaO	1·13	1·45	·39	1·11	1·67
Na_2O	3·54	5·75	5·43	7·30	8·63
K_2O	4·80	4·94	4·08	4·95	5·38
H_2O	·71	1·31	·25	1·04	2·77
P_2O_5	·03	....	....	·04	·06

Calculated as Water-free.

	88	89	90	91	92
SiO_2	75·54	62·14	71·09	62·82	56·59
TiO_2	·30	·90	·48	·31	·37
Al_2O_3	13·23	18·67	11·53	17·77	21·00
Fe_2O_3	·58	3·89	4·59	3·08	3·15
FeO	·40	1·62	1·89	1·82	1·87
MnO	·07	·01	·39	·18	·23
MgO	·30	·47	·11	·49	·61
CaO	1·14	1·47	·39	1·12	1·72
Na_2O	3·57	5·82	5·44	7·37	8·87
K_2O	4·84	5·01	4·09	5·00	5·53
P_2O_5	·03	....	....	·04	·06

Each sum = 100·00.

GROUP XV.

	Dike-rocks.					
	93	94	95	96	97	98
	Minette (Osann and Clarke).	Kersantite (Osann and Rosenbusch).	Vogesite (Osann).	Camptonite (Osann).	Monchiquite (Osann).	Alnöite (Osann and Washington).
No. f Analyses.	10	20	4	15	16	6
SiO_2	49·45	50·79	52·62	40·70	45·17	32·31
TiO_2	1·23	1·02	·54	3·86	1·90	1·41
Al_2O_3	14·41	15·26	14·86	16·02	14·78	9·50
Fe_2O_3	3·39	3·29	3·60	5·43	5·10	5·42
FeO	5·01	5·54	4·18	7·84	5·05	6·34
MnO	·13	·07	·84	·16	·35	·01
MgO	8·26	6·33	8·55	5·43	6·26	17·43
CaO	6·73	5·73	5·86	9·36	11·06	13·58
Na_2O	2·54	3·12	3·21	3·23	3·69	1·42
K_2O	4·69	2·79	2·83	1·76	2·73	2·70
H_2O	3·04[1]	5·71[2]	2·70	5·59[3]	3·40	7·50[4]
P_2O_5	1·12	·35	·21	·62	·51	2·38

Calculated as Water-free.

	93	94	95	96	97	98
SiO_2	50·99	53·87	54·08	43·10	46·76	34·93
TiO_2	1·27	1·08	·56	4·09	1·96	1·52
Al_2O_3	14·86	16·18	15·28	16·97	15·30	10·27
Fe_2O_3	3·50	3·48	3·70	5·76	5·28	5·86
FeO	5·17	5·88	4·29	8·30	5·23	6·85
MnO	·13	·07	·86	·16	·36	·01
MgO	8·53	6·71	8·79	5·76	6·48	18·84
CaO	6·95	6·09	6·02	9·92	11·45	14·68
Na_2O	2·62	3·31	3·30	3·42	3·82	1·53
K_2O	4·84	2·96	2·90	1·86	2·83	2·92
P_2O_5	1·14	·37	·22	·66	·53	2·59

Each sum=100.00 [1] Includes ·61% CO_2. [2] Includes 2·61% CO_2. [3] Includes 2·97% CO_2. [4] Includes 4·35% CO_2.

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Average Specific Gravities of Certain Types.

The average specific gravities of holocrystalline types have been calculated, with results shown in the following accessory table. Most of the determinations were taken from Osann's book:—

—	Number of specimens averaged.	Average specific gravity.
Granite	58	2·660
Granodiorite	5	2·740
Syenite	11	2·773
Monzonite	2	2·805
Nephelite syenite	13	2·600
Diorite	17	2·861
Gabbro	19	2·933
Olivine Gabbro	4	2·948
Anorthosite	6	2·715
Peridotite	21	3·176
Essexite	2	2·862
Theralite	3	2·917
Malignite	4	2·884

Source of Magmatic Heat.

Before a genetic classification of igneous-rock bodies can be worthily undertaken, attention must be given to the problem of magmatic heat. Needless to say, its full discussion is impossible in this report, but a summary statement of the matter as understood by the writer will make clearer the following chapters.

The reader will recall various older attempts to account for volcanic heat; some by exothermic chemical reactions underground; others by assuming a sufficient concentration of the heat produced in the crushing of rock during the folding of mountain chains. Such suggestions have certain value as partial explanations, but have so far failed to account for the largest part of the heat contained in extrusive and intrusive bodies. At present, most geologists are inclined to believe in the very oldest of the scientific explanations, namely, that magmatic heat is chiefly a residual of the primary heat in a cooling planet.

According to the Laplacian statement of the nebular hypothesis, the earth was originally a small star, incandescent at its surface and centrally very much hotter than the hottest known lava. The crusting and continued cooling of such a spheroid must give isothermal surfaces rather closely parallel to its own surface. On this hypothesis the depth at which ordinary rock-matter is hot enough to be eruptible, because molten, is approximately the same all around the globe, and for a vast period of time only a few miles, or tens of miles, below the surface.

According to Chamberlin's statement of the planetesimal hypothesis, the earth has been a dark body, cool enough to bear a water-ocean and living creatures, from a remote time when the planet's diameter was considerably less than at present. The continued accretion of planetesimals has since enlarged the Earth. The compression of the interior of a planet constantly solid is supposed to have generated heat sufficient to explain vulcanism and the observed thermal gradient near the Earth's surface.

'As the conduction of heat through rock is exceedingly slow, the central heat may be assumed to have continued to rise so long as the infall of matter caused appreciable compression. In the same way, heat was generated progressively in the less central parts, and these parts also received the heat that passed out from beneath. It is assumed under this hypothesis that the degree of interior compression stands in close relation to interior density, for while there would probably be some segregation of heavier matter toward the center and of lighter toward the surface by means of volcanic action and internal rearrangement under stress differences, the interior density is regarded as due mainly to compression. The distribution of internal pressure and density generally accepted is that of Laplace, who assumed that the increase of the density varies as the square root of the increase of the pressure. This law gives a distribution of density that accords fairly well with the phenomena of precession of the equinoxes, which require that the higher densities of the interior shall be distributed in certain proportions between the center and the equatorial protuberance whose attraction by the sun and moon causes precession. The increases in pressure, density and temperature have been computed as follows by Mr. A. C. Lunn, the average specific gravity of the earth being taken at 5·6, the surface specific gravity at 2·8, and the specific heat at ·2. . . . . .

'The accretion hypothesis assumes that, during the growth of the earth, large amounts of heat were carried by volcanic action from deeper horizons to higher ones and to the surface, and that this still continues at a diminished rate. It assumes that whenever the interior heat raised any constituent of the interior matter above its fusing-point under the local pressure, it passed into the liquid state, *and was forced outwards by the stress differences to which it was subjected,* unless its specific gravity was sufficiently high to counterbalance them. It is conceived that the more fusible portions were liquefied first, and that in so doing they absorbed the necessary heat of liquefaction and began to work their way outward, carrying their heat into higher horizons and temporarily checking the development of more intense stresses in the lower horizons. They thus served to keep the temperature there below the fusion-point of the remaining more refractory substances. Meanwhile the extruded portions were raising the temperatures of the higher horizons into which they were intruded or through which they were forced to pass.'*

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* T. C. Chamberlin and R. D. Salisbury, "Geology," New York, 1906, Vol. I, pp 564-567.

On the Chamberlin hypothesis the isothermal surfaces within the earth are roughly parallel to its own surface because of the progress of the central heat-wave along all radii, but the temperature of molten lava at atmospheric pressure (say, 1100° C.), is to be found, on the average, at a depth of about 400 miles. The difficulty of understanding how magma can pass through so thick a shell is not removed by Chamberlin's suggestion that liquid 'tongues' of the more fusible rocks are forced through the shell by the tidal kneading of the earth. The differences in the so-called 'fusibility' of the principal igneous rocks are really not great, the 'fusion points' for dry melts generally lying between 1000° C. and 1150° C. When water and other volatile fluxes enter the melts the differences may be still less. As a matter of fact the acid, more difficultly melted rhyolites are often directly associated with the easily melted basalt in the same region and in the same petrogenic cycle. If differential 'fusibility' controls the eruption of magma, the material of great depth must be something different from the known mixtures of silicates in nature.

The geologist is mainly interested in the planetesimal hypothesis as it bears on the condition of the earth since the time when it approached its present size through accretion. When the planet has reached that size it is entirely possible that the central heat has increased beyond the critical temperatures of all known substances. This would in turn imply complete change in the dynamics of the earth. The change of state in the core implies: (1) enormous gaseous pressures; (2) the differentiation of the original miscellaneous materials into a system of fluids which would be stable under the new conditions; with (3) an inevitable transfer of hotter, because originally more centrally placed, material to higher levels; (4) the consequent melting of the solid matter overlying this new gaseous system; (5) the expected evolution of the more volatile matter at temperatures high enough to further the melting of the solid overlying shell. In fact, there is in Chamberlin's hypothesis no known reason why the whole planet from surface to center should not become fluid in this relatively late stage in its development. For the period including what is generally called geological time there would, in this view, be no essential difference between the gas-nebula and planetesimal-nebula hypotheses.

In any case the analogy of the sun and other stars, the yet closer analogy of the 'semi-sun,' Jupiter, and, indeed, the face of the moon, all suggest that the earth was once wholly fluid in its surface shell at least. The plain evidences of such present or former superficial fluidity in other members of the solar system are not sufficiently regarded by any hypothesis which denies a similar stage in the earth's history.

According to either of the two rival cosmogonies now holding attention, magmatic heat may be chiefly explained as an inheritance from a primitive condition of the earth when it was fluid at the surface. In either case a crust was formed through loss of heat by radiation, with a magmatic stratum beneath. The calculations of Kelvin and others show that the temperature of any volcano is to be found at a relatively shallow average depth within the earth. Extrapolation on the normal temperature gradient (3° C. rise per 100 metres of depth) gives a temperature of 1200° C. at the depth of 40 kilometres (25 miles). Since both conductivity and diffusivity for heat are notably lowered by increase of temperature, it is quite possible that the temperature gradient steepens with depth. In that case a temperature of 1200° C. may reign at an average depth of less than 40 kilometres.

On the other hand, it is clear that the temperature gradient is, in part, the result of radioactivity in the rocks of the earth's crust, and that this subatomic energy is one cause of magmatic heat. The relative importance of the primitive heat and of that due to radioactivity is at present beyond even a guess. The subject is full of difficulties and geologists must wait for the physicists to make the balance true. Meanwhile, the analogy of the sun and the other planets can be trusted to enforce the belief in primitive heat.

Composition of the Substratum—the General Earth-magma.

In several papers the writer has expressed the opinion that the substratum, which before injection is at least potentially fluid, and after injection is really fluid, is of basaltic or gabbroid composition. The basaltic substratum is conceived as the heat-bringer in all igneous activities since the later pre-Cambrian periods. Since the time when the Keewatin greenstones were extruded, if not from a still earlier period, the only primary magma has been the basaltic. All other magmas are conceived to be either differentiates from basalt; or, secondly, direct products of the solution of the over-lying crust; or, thirdly, differentiates of those syntectic* products. The writer has found that these views are, in part, as old as Bernhard Cotta's 'Geologische Fragen,' published in 1858, though Cotta did not, and could not in his day, appreciate the importance of magmatic differentiation.

Cotta's main idea, which has been independently reached by the present writer through a study of eruptive fields and of the more modern geological literature, is basal to the following considerations on the theory of igneous rocks. The grounds for belief that basalt has been the universal magma since a pre-Cambrian epoch should be briefly restated.

1. All of the first-class lava floods of the world, from the late pre-Cambrian to the Pleistocene, are composed of basalt remarkably uniform in chemical character. These floods were erupted through fissures. The high fluidity of the basalts, in the act of eruption, is shown by the great area covered by even the thinner flows. Yet in most cases this evidently superheated lava has not dissolved any appreciable amount of the schists, gneisses, granites, or sediments through which the fissures were opened. The basalt of fissure eruptions is not a syntectic. We can only conclude that the lava channels within the generally acid crust were always narrow and that the basalt was extruded rapidly. Such is the orthodox view. The superheat indicated by the extrusion and form of the flows is an *à priori* ground for believing that these basalts are not the product

* "Syntectic" is Loewinson-Lessing's useful name for the mixture of rocks due to their melting together, thus forming a mutual solution.

of post-Archean differentiation, since magmatic differentiation is very probably an incident of cooling nearly to the solidification point.

Yet more telling is the argument that, if the basalt of the greater lava floods is the product of a differentiation nearly contemporaneous with extrusion, we should expect to find the other pole of the differentiation in immediate association. This pole must be more acid than basalt, for no known earth-magma can be fairly suggested which would, by splitting, give basalt as the acid pole. The commoner peridotites are probably differentiates of basaltic magma and, in any case, cannot be regarded as the parent of basalts. If, then, basalt is the basic pole of magmatic differentiation we should expect to find large effusions of the contemporaneous, more acid differentiate in the greater lava fields of the globe. The more acid differentiate should normally overlie the basalt in the magma chamber, and must in most cases be erupted through the opening fissures before the basalt could reach the surface. The only escape from that conclusion is to be found in the postulate that the acid differentiate had completely solidified before the basalt was poured out. This postulate is plainly inconsistent with geological experience in the smaller volcanic terranes, where both poles of magmatic differentiation are so regularly found in the extruded lavas. Yet in the Columbia and Snake River lava fields of America, in the similarly vast field of the Deccan, as in the ancient field covered by the Purcell Lava, there is no acid differentiate to match the basic differentiate, basalt, of any of the fissure eruptions. The simple and probable conclusion is that the basalt of all the vast lava fields is pure, undifferentiated material from the earth's interior.

If so, it seems to follow that no different kind of fluid rock-matter overlies the basalt of the substratum. If, for example, a primary liparitic magma overlies it, the method of eruption of the pure basalt through the liparite to the earth's surface would be, to say the least, inconceivable.

2. The association of chemical types at 'central eruptions' (volcanic cones and craters), is generally much more complex than that characteristic of the greater lava plateaus. Two of the principal reasons for this are apparent. As compared with the feeding sheets of lava in fissure eruptions, the lava columns of cones stand longer in their vents. The vents of central eruptions are kept open because of the emanation of gases from the feeding magma chamber. At the actual opening the lava is sometimes seen to be superheated (e.g., at Hawaii, Savaii, etc.) A moderate assimilation of the walls of the vent is to be expected in the earlier stage of a volcano's history. Syntectics may be formed; the primary magma may be subject to specially marked differentiation through fluxing, or because of inoculation; and the syntectic may be differentiated. Among so many possibilities it is little wonder that the sequence of eruptive types is a variable one. After a vent has long afforded passage to lava, so as to build up a first-class cone, the volcano approaches its limital height and also the stage of extinction. Assimilation is then checked, the formerly enlarged vent is narrowed by gradual freezing, and the final extrusions are composed of primary magma or of its own differentiates. This appears to be the best explanation of the general fact that the latest lavas of the largest volcanoes, like Etna or Chimborazo, are basalts or pyroxene andesites. As noted below, there are

reasons for believing that pyroxene andesite is a direct differentiate of basalt. The greater central-eruptions, like fissure eruptions, seem, therefore, to indicate basalt as the primary eruptible material under part, at least, of each continent and ocean basin.

3. A tolerably wide study of geological maps and literature shows that basaltic magma is the only one known to recur in all the larger petrographic provinces of the world. That this magma is represented in intrusive diabase, porphyrite, or gabbro, instead of lava flows is, of course, a matter of indifference. Basaltic magma in one of these forms has given rock bodies in each of the alkaline provinces, such as Madagascar, Kola, Bancroft area (Ontario), Montana, Tasmania, Christiania Region, etc. Similarly, no large granitic terrane is free from intrusion of this basic matter. Granite is the only possible rival to basaltic magma with respect to universal occurrence; yet in the half of the earth's surface covered by the majority of the oceanic islands, granitic or liparitic rocks are unknown. On their thousand-mile zone of fissures the volcanoes of the Hawaiian archipelago, including the greatest in the world, have been built up of essentially basaltic material. Cross's ' biotite-trachyte ' of Hawaii may be regarded as an acid phonolite and, like other alkaline rocks now known in the islands, may be explained as a differentiate of the olivine-basalt type with which it occurs.

The same law of the steady accompaniment of persilicic (granitic) and alkaline rocks by rocks of basaltic composition has apparently held through all the recognized geological periods since Keewatin-Huronian times. The full significance of this law of distribution cannot be attained until the origin of granitic, alkaline, intermediate, and ultra-basic eruptives is understood. But we may here note that the secular uniformity of the basaltic magma, irrespective of its association with these widely divergent types, can be credited to magmatic differentiation only through an entire disregard of the known laws of magmatic solutions. Since it is also improbable that so constant a type as the basaltic magma is due to assimilation of solid rocks in any other magma, known or unknown, we are left with but the one alternative, that the basaltic magma is primary and of general distribution beneath all the continents and seas. This, too, has been the condition since the relatively late stage in the pre-Cambrian when the Keewatin lavas were poured out on the earth's surface.

4. Most of the other magmatic types can be explained as secondary and due to the solution of a primary acid earth-shell and of sedimentary rocks in the primary basalt, the syntectics generally undergoing differentiation before the visible rocks were crystallized. The discussion of this thesis forms a large part of the following theoretical sections of the report. It is referred to here merely to point the fact that the non-basaltic magmas of post-Cambrian time at least occur in such volume and relations as are appropriate to the idea here discussed.

5. Pyroxene andesite, which in volume is probably only second to basalt among the volcanic types, seems to be best regarded as a direct differentiate of basalt. If so, the present argument, so far as derived from an estimate of relative volumes, is strengthened.

PRIMARY ACID SHELL OF THE EARTH.

The natural supposition that a once molten earth would have become stratified through density has been made probable by the more recent studies of silicate melts and of natural magmas. Irrespective of pressure, the primitive differentiation of earth-magma would give liquid layers of absolute density increasing with depth. The increase might be gradual or it might occur in relatively sharp changes from layer to layer, each of which was immiscible with its neighbour at the ruling temperature. According to the second view each layer would be expected to have a fairly uniform composition. If one of the layers was basaltic, as implied in the preceding section, the overlying layers were lighter and presumably more acid than basalt. We may now briefly examine the view that the uppermost primary layer, or earth-shell, was granitic in composition.

Every worker in the pre-Cambrian sediments is struck with the predominance of quartz fragments. Granites or gneisses are certainly the principal sources of such silicious material. When we reflect that the earliest known sediments are thus quartzose; that the total thickness of the pre-Cambrian quartzose sediments, as measured in eastern Canada, British Columbia, Finland, and elsewhere, runs into tens of thousands of feet, we may be sure that the lands prevailing throughout most or all of recorded pre-Cambrian time were of granitic (gneissic) composition. Such terranes are exposed on an enormous scale in a few parts of the earth and are fairly to be understood as forming the greater part of the present continental plateaus. The film of sedimentary rocks on these plateaus averages so thin that no essential doubt can remain as to the general character of the surface shell through which Paleozoic and later igneous eruptions have taken place. A rough quantitative study of available maps shows that this shell is, on the average, everywhere of granitic composition. Two lines of evidence thus converge to the belief that from the earliest time recorded in the pre-Cambrian sediments to the time of the great Cambrian overlap, the surface rocks of the globe were dominantly granitic (or gneissic). Can we go further and hold that the first stable shell formed on the cooling globe was of similar granitic composition? The speculative attempt to answer the question has some value.

Dutton suggested that the visible granites, gneisses, syenites, etc., were produced by the remelting of sediments derived from a general and primordial basaltic shell, implying that the lands of most of pre-Cambrian time were basaltic. He writes:—'Chemical considerations of a cogent character lead up to the inference that primordial magma ought to possess a constitution similar to rocks of the basaltic group, though perhaps somewhat less ferruginous (?), and that it should be nearly homogeneous.' And again:—'We know of no natural processes capable of separating the more acid parts of such a magma except the chemistry of the atmosphere acting at temperatures far below the melting-points of the silicates. We have the results of that process in the quartzites, granites, gneisses, and syenites among the silicious rocks; and the limestones and dolomites among the basic rocks; with argillaceous rocks as the residuum of the decomposition.'*

The idea that basalt, as a 'comprehensive or synthetic' rock, might have given the world's granites through weather-leaching and remelting of the leached-out products can be tested quantitatively with a fair degree of confidence in the result. The ratio of soda to potash, in the average basalt, is about 3·16: 1·55. The ratio in average granite is about 3·31: 4·10; and in the average pre-Cambrian granite, about 3·26: 4·53. (See Columns 1 and 4 of Table XLIV). Even if all the potash remained among the residual products of the weathering of basalt, it would take nearly three weight units of basalt to make a weight unit of granite, according to Dutton's principle. All the soda, or say three per cent of two weight units of basalt, goes in solution to the sea. Many granite batholiths are known to be at least two miles deep and are probably much deeper. It is safe to postulate that 40,000,000 square miles of the earth's surface is underlain by granite or by the average pre-Cambrian terrane, itself a granite in composition. If we hold that their combined mass is of the minimum average depth of two miles, it follows that at least 200,000,000 cubic miles of basalt, or enough to cover the planet one mile deep, must have been weathered to produce the whole granitic mass. About two per cent, by weight, of the basalt is sodium carried in solution to the ocean. This addition alone would charge the ocean with three times as much sodium as it actually contains. Since nearly all the sodium which has ever entered the ocean is still there in solution, the vast excess calculated shows, without allowing for other sources of oceanic sodium, that the main assumption cannot be true.

The only remaining interpretation of the acid basement complex of the continental plateaus recognizes in it the material of the earth's primary surface shell. This shell has been denuded, metamorphosed, and largely remelted in the huge batholithic invasions of the Laurentian type. Little or none of the visible pre-Cambrian terrane directly represents the unmodified, original crust, but, in spite of all its vicissitudes, the terrane seems to have retained the average chemical composition of the primary acid shell.

Our speculation leads, thus, to the conception of an early separation of the earth's outer magmatic layer into two shells; the underlying one basaltic in composition, the overlying one granitic in composition. If these are the poles of a gigantic process of magmatic differentiation, the original magma must have been of some mediosilicic type. If it be arbitrarily assumed that the two poles of this differentiation were formed in equal masses, the original magma must have had a composition much like the average augite andesite or the average diorite. The following table (XLV) shows the comparison of the mean of the average pre-Cambrian granite and average basalt, with the average diorite and average augite andesite; each average being computed from a large number of analyses, and recalculated as water-free.

* C. E. Dutton, Report on the Geology of the High Plateaus of Utah, Washington, 1880, pp. 124-125.

TABLE XLV.—*Comparison of average analyses; granite, basalt, diorite, and andesite.*

	1	2	3	4	5
	Average pre-Cambrian granite.	*Average basalt.*	*Mean of 1 and 2.*	*Average diorite, including quartz diorite.*	*Average augite andesite.*
Number of Analyses.	47	198	....	89	33
SiO	71·56	49·87	60·71	59·19	58·65
TiO_2	·48	1·38	·93	·81	·80
Al_2O_3	14·20	15·96	15·08	16·51	17·67
Fe_2O_3	1·47	5·47	3·47	3·02	3·85
FeO	1·65	6·47	4·06	4·17	3·69
MnO	·18	·32	·25	·13	·22
MgO	·59	6·27	3·43	3·93	2·90
CaO	1·98*	9·09	5·54	6·47	5·92
Na_2O	3·26	3·16	3·21	3·39	3·60
K_2O	4·53	1·55	3·04	2·12	2·40
P_2O_5	·10	·46	·28	·26	·30
	100·00	100·00	100·00	100·00	100·00

*Includes ·08% BaO and ·02% SrO.

It is further significant that the average composition of the ground-mass of four typical augite andesites is nearly identical with the average pre-Cambrian granites, as it is with the average granite of all ages; these averages being calculated as water-free. A second step in this far-flung guess as to the origin of the acid shell is prompted by the facts illustrated in Table XLVI. Such a glance at a hypothesis of origins cannot vitally affect the question as to the *existence* of the acid earth-shell—here the essential point in the general theory of the igneous rocks.

TABLE XLVI.—*Comparison of average analyses; granites and ground-mass of augite andesite.*

	1	2	3	4
	Ground-mass (base) of augite andesite.	*Average pre-Cambrian granite of the world.*	*Average pre-Cambrian granite of Sweden.*	*Average granite of all periods.*
Number of Analyses.	4	47	114	236
SiO_2	69·31	71·56	70·33	70·47
TiO_2	....	·48	·54	·39
Al_2O_3	17·11	14·20	13·86	14·90
Fe_2O_3	2·15	1·47	2·19	1·63
FeO	·60	1·65	1·89	1·68
MnO	....	·18	.26	·13
MgO	·70	·59	·85	·98
CaO	2·63	1·98*	2·22	2·17†
Na_2O	3·20	3·26	3·19	3·31
K_2O	4·30	4·53	4·41	4·10
P_2O_5	....	·10	·26	·24
	100·00	100·00	100·00	100·00

* Includes ·08% BaO and ·01% SrO. † Includes ·06% BaO and ·02% SrO.

The two comparisons suggest the speculation that the primitive acid shell was derived from an andesitic magma, from the upper part of which most of the femic material settled and enriched the lower part in the same oxides. The complete mixing of these femic constituents in the hotter andesite below is conceived to produce the basaltic shell.

As far back as Keewatin time at least the acid shell seems to have been largely or wholly solidified so as to be capable of fissuring, thus permitting the basaltic Keewatin lavas to be extruded. With respect to all Keewatin and post-Keewatin igneous action the basalt of the substratum has been hitherto called 'primary,' but it is evidently possible that it was derived from a general pre-Keewatin magma. The substratum basalt will still be referred to as primary, for it bears the primeval heat and has suffered no appreciable chemical change of composition since the oldest of the recognized pre-Cambrian basalts were erupted.

ABYSSAL INJECTION OF MAGMA.

Proceeding on the assumptions: first, that the magmatic heat is chiefly an inheritance from primitive times; secondly, that rock eruptible because hot enough to flow at low pressure, is everywhere present at moderate depths below the earth's surface, we are in accord with the nearly unanimous opinion of geologists. If the observed temperature gradient is specially steep because of the concentration of radioactive matter in a thin surface shell, the thickness of the crust may be as much as 100 miles or more. In any case, the depth of the bottom of the crust is probably much greater than the depth of any exposed intrusive contact at the time of the intrusion of that body. The magma must penetrate at least 15 or 20 miles of crust before it reaches such levels as those registered in the known, actually seen, igneous bodies.

How this penetration of the lower and thicker part of the crust takes place has always been a difficult problem. The idea that the primary rock-magma melts its way to the surface, or even to the levels of now visible intrusive contacts, may be dismissed. The very great superheat demanded can scarcely be admitted for an earth-shell so close to the surface. The only alternative seems to be the usual conception that the magma always traverses the lower and thicker part of the earth's crust along mechanically opened fissures. To this process the name 'abyssal injection' may be given.* It is to be regarded as the prelude to vulcanism, or to intrusion, whether of laccoliths, dikes, or batholiths.

For the shell of eruptible rock-matter we have the old, appropriate name 'substratum,' as employed by Fisher, Lowthian Green, and others. In most problems of igneous geology it is not necessary to decide on the question as to the rigidity of the substratum with respect to such cosmic forces as the earth tides. Since, however, the latent heat of crystalline silicate rocks is about one-fifth of their total melting heat when just molten, the simplest supposition is that the substratum is not crystallized. The transformation of a crystalline substratum into fluid magma at the lower openings of abyssal fissures is evidently much more difficult than the change of an isotropic, highly rigid liquid into a readily eruptible, distinctly fluid magma. The many attacks on the hypothesis of a liquid substratum have failed to disprove it, because there has been general neglect of the view that, under great pressures, liquid rock, though very hot, may rival crystalline rock in rigidity.

The idea of a fluid substratum has often been dismissed by authors because of the observed independence of the vents during the simultaneous activity of Kilauea and Mokuaweoweo (Mauna Loa), in Hawaii. It is held that, if the two lava columns rise from a common liquid substratum, the level of the higher column must, by simple hydrostatic action, be kept at the general level of the lower. The actual equilibrium is kept with one column some 9,000 feet taller than the other. Attempts have been made to explain this contrast in levels by a difference in density of the two columns; but there is nothing in the known facts to uphold the suggestion. On the other hand, the field evidence in Hawaii favours the belief in the present independence of the two vents. There is something to be said for the hypothesis that the lava pit at Kilauea is the opening in the roof of a large laccolith, which has been injected into the old lavas of Mauna Loa. The freezing of the dike feeders of the laccolith would isolate

* R. A. Daly, American Journal of Science, Vol. 22, 1906, p. 195.

it, so that henceforth Kilauea and Mokuaweoweo are independent. As yet this suggestion cannot be proved, but it has weight encugh to indicate the need of caution in drawing conclusions regarding the non-existence of a fluid substratum beneath the island of Hawaii. Similar care should be taken in discussing the independent levels of lava in other pairs of volcanoes.

The conditions of abyssal injection have been partially discussed by the writer in a special paper.* Its aim was to state the consequences of the doctrine of the 'level of no strain' in a cooling earth, as these bear on magmatic intrusion. Abyssal injection was explained as due to the peculiar state of the 'shell of tension,' which because of its very nature permits of ready splitting by intruded magma. While many facts seem to agree with the hypothesis, several of its premises are unproved; so that now, as at the time of publication, the idea is in the writer's mind largely a matter of pure speculation. The advantage of such speculation is that it sharpens the scrutiny of the hypothetical premises. These are the subject of observation and experiment, each of which must show improved results as all alternative explanations are kept in mind during an investigation. Meanwhile, explanation is not proof, and geologists must be content, for a time, to regard abyssal injection as a fact, mysterious as it is true. (See pages 572 to 575.)

Each abyssally injected body represents an 'intercrustal magma-basin.' In general, the 'shell of compression' will not readily allow of the passage of magma to the earth's surface, so that the magma would often rise but little above the 'level of zero strain.' The injected body retains physical connection with the substratum and stands above it in vertical form, like a dike, though the size may be batholithic in many cases. Such bodies are conceived to be the proximate sources of the extrusive and intrusive rocks with which the field geologist has to deal.

Origin of Volcanic Action.

Volcanic action may be defined as the working of the extrusive mechanism which brings to the earth's surface rock-matter or free gas, initially at the temperature of incandescence. The mechanism includes: the localization, opening, and shaping of the vent; the persistence of a vent as an open channel during seconds, days, years, or milleniums; the conditions for lava outflow, for gas and vapour outflow, and for the separation of gas or vapour from lava; the conditions leading to the periodicity of eruption at central vents; and those leading to chemical variation in the erupted magma. This section is intended to sketch in very brief form a theory of volcanic action, founded on the principle of abyssal injection. It is planned to develop the theory at greater length in a separate publication.†

According to the views expressed in modern text-books of geology, the emission of incandescent matter at the earth's surface takes place either in the

* American Journal of Science, Vol. 22, 1906, p. 195.

† Issued, since forwarding the manuscript of this report, in Proc. Amer. Acad. Arts and Sciences, Vol. 47, 1911, pp. 47-122.

form of fissure eruptions or in the form of central eruptions. The writer believes that a third method should be entertained as a possibility, namely, by the partial or complete foundering of batholithic roofs. The relation of each of these three phases of volcanic action to abyssal injection may now be outlined.

Fissure Eruptions.—The regional lava floods, known to have emanated from simple fissures in their underlying terranes, range in date from the pre-Cambrian to the present. As we have seen, they are, without exception, of basaltic composition. Such magma must be exotic, that is, it cannot be explained as due to the refusion of material from the earth's acid or sedimentary shells. It is the only lava (extrusive magma) to which a secondary origin cannot theoretically be ascribed. But the very low original slopes of the flows (very often inclined at much less than one degree from the horizontal plane) and their great lengths show that the basalt of fissure eruptions is notably superheated. Such temperature is appropriate to assimilation of foreign rock. That the solution of pre-Cambrian gneisses or of other rocks has not taken place in sensible amount must have either of two meanings. It may mean that the various abyssal injections underlying the lava field are narrow, with widths to be measured in feet or tens of feet, but not in many thousands of feet. Or failure to assimilate may be due to special rapidity of injection, with simultaneous extrusion; for solution of foreign rock must take considerable time. The observed average size of the feeding channels (dikes) in the great lava fields of the western United States, of northwestern Europe, of India, and other regions corresponds with the former conclusion. The vast Icelandic flow of 1783 and the nature of the individual flows in every pre-historic lava field show or at least suggest that each extrusion has been rapid. The controlling condition for the lack of assimilation is probably the narrowness of the abyssal injections, at least in the part traversing the sedimentary and acid shells of the earth.

The fissures need not be planes of strong, or even discernible faulting. For example, the Purcell Lava, covering many thousands of square miles, issued quietly from many cracks in the Siyeh-Kitchener sea-bottom, and covered the muds and sands with a continuous sheet of basalt, which evidently flowed on a flat, practically unbroken surface. This eruption illustrates, in fact, the very common association of fissure eruption with downwarps of the broad, gentle, geosynclinal order. Whether the down-warping is the effect of abyssal injection, as suggested by the writer in a published paper,* or whether the abyssal injection and surface outflow are the effect of down-warping, are important questions which will not be discussed in this place.

The effusion of a basaltic flood is generally ascribed to the mere squeezing out of the magma from beneath a cracked and sinking Earth-crust. Yet some force may also be available from the expansion of the substratum material as it rises to levels of greatly lessened pressure. This expansion is of two kinds—that of the lava regarded as gas-free, and that of the gases separated from it in bubble form. If the expansional energy of the liquid proper is not all used up in driving asunder the walls of the injected body, some of that great force

* R. A. Daly, American Journal of Science, Vol. 22, 1906, p. 195.

is available for extrusion. As magma nears the surface, the separation of the dissolved gas must still further increase the volume and tend to cause outflow at the surface. The relative importance of these three conditions for extrusion is by no means apparent.

The fact that the great bulk of visible igneous rock is intrusive, and the related fact that most of the larger Paleozoic and later injections have not extended to the surface, suggest that the upper part of the Earth's crust has long been comparatively difficult of penetration by abyssal magma. It seems fair to hold that a leading cause of this relative impenetrability is the state of compression in the outermost shell of the crust. The compressive stress is relieved by an orogenic paroxysm. After each paroxysm tensions in the same shell are produced by the cooling of the rocks which have been heated by shearing. For a double reason, therefore, fissure eruptions should be more numerous and of greater volume in periods subsequent to strong mountain-building. This expectation is fairly matched by the facts of geological history, as shown in the accompanying table:—

Locality.	Date of Fissure Eruption.	Preceding Orogenic Period.
Lake Superior District	Keweenawan	Close of the Animikie.
Rocky Mts. at 49th Parallel	Middle Cambrian ?	Early Middle Cambrian ?
British Islands	Carboniferous	Devonian.
Appalachian Mts.	Triassic	Close of Paleozoic.
Deccan, India	Cretaceous (or Early Tertiary ?)	Late Triassic (also later ?)
Great Rift, Africa	Cretaceous (Kaptian series)	" "
Washington State	Eocene (Teanaway basalt)	Close of Laramie.
N. W. Scotland	Oligocene (Lower Miocene)	?
Iceland	Miocene	?
Washington State	Miocene (Yakima basalt)	Close of Eocene.
Great Rift, Africa	Miocene ?	Tertiary (Alps, &c.)
Great Basin, U.S.A	Pliocene	Late Miocene.
Snake River, Idaho	"	"
Hauran, Syria	"	Tertiary.
Iceland	Pleistocene and Recent	"

Eruption through Local Foundering.—When the width of an abyssal injection is increased beyond a critical value, the body may have sufficient thermal energy to enlarge its chamber by incorporating roof and wall rocks. The result is a batholith. The average batholith, at *exposed* levels, is granitic because granite represents the stable and least dense differentiate of the average syntectic.

The integrity of the batholith's roof is evidently threatened in two ways. It is thinned during the absorption of the roof-rock by the molten magma. The latter might work its way to the surface through piecemeal stoping, which should continue until a large area of the batholithic roof has disappeared. On the other hand, it is also possible that part or all of the roof might, under special conditions, founder *en masse* in the less dense magma. In either case true volcanic action is produced. Such wholesale or piecemeal foundering would not fairly be called fissure eruption, though it might be accompanied by lava floods emitted from fractures in the roof-rock surrounding the foundered area. The level of the lava in the area of foundering would, in form, resemble a plateau (fissure) eruption, but the lava would here be generally liparitic rather than basaltic as in the majority of plateau eruptions. Moreover, the liparite would form a continuous mass, merging downwards into granite, and thus not a series of superposed distinct flows. According to the topography, the lava of the foundered area might flood valleys outside that area. If the hydrostatic adjustment were accomplished in stages, successive superposed flows might be caused in the valleys.

Though the field evidences do not seem to favour this conception for most exposed batholiths, it should be retained as a possibility in some cases. In general the problem has a peculiar difficulty. The evidence for local foundering is in special danger of being obliterated. The glassy or scoriaceous phase of the 'batholith' will necessarily be eroded away before the granitic phase can be exposed. The liparitic phase need extend to a depth of no more than a few hundred feet, where it would rapidly merge into the holocrystalline phase. Therefore, comparatively little time would be required to remove the original surface phase. The geologist, studying the erosion-surface, might have no inkling that the 'batholith' had not been completely covered by a roof of country-rock. The former existence of a roof cannot be assumed simply because a 'batholith' has a holocrystalline structure.

The application of this deductive scheme of thought to actual examples cannot be described in this chapter; it will be made in the special paper to be published. The possibility that the unrivalled liparite plateau of the Yellowstone Park was formed in consequence of local foundering will there be discussed in some detail. Other cases, in Massachusetts and elsewhere, will be used as parallels.

Central Eruptions.—In many abyssal injections the magma does not directly reach quite to the Earth's surface, though it may ultimately cause true volcanic action in the form of 'central eruptions.'

Mere hydrostatic outflow of magma will not explain the persistence of activity at a central vent; at Kilauea there is no overflowing, though its lava lake is probably the most persistently active on the globe. Recurrent explosion allowing an intermittent rise of new, hot magma in the vent is clearly unable to supply heat fast enough; Kilauea is not explosive. Actual calculation of the convective gradient shows how powerless thermal convection is to supply the necessary heat at the surface. Yet continued activity means victory of the lava column in a struggle with cold.

More promising is the conception that the heat of the underlying magma chamber is transferred to the crater by another kind of convection, that due to the generation of gas bubbles in the lava column. At the depth of a few hundred feet, bubbles of individual mass corresponding to normal lava vesicles must have very small volume. For that reason, as well as through the considerable increase of magmatic viscosity with pressure, such bubbles must rise very slowly. A special aggregate or swarm of them would therefore exert a strong buoyant effect on the mass of magma in which they are entangled. The principles of fluid dynamics show that the mass of specially vesiculated magma would rush up the conduit at comparatively high speed. Arrived at the surface, it parts with much of its dilating gas, grows heavier, and sinks. Its place is taken by a later uprushing mass; the rhythmic action is more or less continuous. Since a gas phase and a liquid phase are essential to the process, this powerful method of circulation may be called 'two-phase convection.'

Again the writer must here omit detailed arguments on a subject which seems to him of considerable importance. Suffice it only to remark, first, that two-phase convection is visible throughout the activity of the lava lakes of Hawaii and Savaii, and has been observed in the lava of the craters at Vesuvius and Etna. Secondly, the hypothesis seems to be well supported by actual calculation of its efficiency, as will be indicated in the special paper.

That paper will also sketch the arguments for the view that much of the heat emanating at a central vent is not primary but is the product of chemical reactions, chiefly among the gases, in the lava column. Herewith we have partial explanation for the long lives of many volcanoes. Their vents are kept open, partly because of the manufacture of heat in the conduit by exothermic gaseous reactions; and partly through the convective transfer of heat by the formation of a gas phase in the lava column. Since in both respects the presence of magmatic gases is vital to the continuance of activity, this view of the essential nature of eruptivity at central vents may be called the 'gas-fluxing hypothesis.'

Gas-fluxing explains the localization of the vent. In the parent abyssal injection the gases rise and collect about *points* in the roof of the magma chamber. The highest point in the roof will, in the end, attract the rising gas most effectively. As the gas tension increases, the strength of the roof at the point of special gas accumulation may be overcome and an explosion opens a vent (a diatreme) to the Earth's surface. Or, if a fissure is opened above the point of gas accumulation, it may be enlarged to vent size, first by outrushing hot gas and then by two-phase convection.

In the process of time every central vent must become more or less perfectly cylindrical—a solution form. In this respect, as well as in the small size of these vents, even in the mightiest cones, the gas-fluxing hypothesis is supported by the facts of nature.

Gas-fluxing also explains the periodicity of the activity at central vents. A long period of activity tends to exhaust the supply of gas in the conduit and immediately below it, that is, in the uppermost part of the magma chamber. Hence two-phase convection tends to slow down. The powerful radiation in the crater finally causes the lava to freeze at the surface and a solid plug of greater or less depth is formed. This plug must be removed before activity can be resumed.

The removal of the plug is not due primarily to explosion. A volcano may be dormant for scores of years, so that not even mild solfataric action persists in the crater. In such a case the plug must be thick. On the average it is much stronger than the mass of tuffs surrounding it. Without a preliminary thinning of the plug we should expect explosion to open a vent on the side of the cone rather than at the old crater. In point of fact, the symmetry of great cones like Etna, Fuji-yama, or Mayon, together with the known history of many cones, shows that the greater activity is normally renewed at the original vent.

This behaviour is intelligible if it be granted that magmatic gases continue to rise from the depths and collect under the plug. The temperature of the lava column slowly rises because of the exothermic chemical reactions and because of the compression of the accumulating gas, which steadily increases in tension until it reaches a certain maximum value. The plug is thereby slowly melted at the bottom. After sufficient melting has occurred, the magma, with its newly acquired tension, becomes capable of bursting the plug with one or more major explosions. A new period of activity is initiated; it will last until the special accumulation of gas at the top of the general magma chamber is largely exhausted.

This rhythmic action is, of course, subject to the complicating influence of the solution of foreign matter by the magma, in the conduit or in the feeding chamber, or in both. The material absorbed may be volatile, e.g., vadose or resurgent water, and will therefore increase the gas-tension in the vent. Wholesale evisceration of the volcanic pile may occur, so that a Somma cone becomes a caldera floor, later to be surmounted by a Vesuvius cone.

In general, each central vent increases in explosiveness toward the end of its life. Whether juvenile or resurgent, the gases have increasing difficulty in escaping into the air. This means, of course, increase in the magmatic viscosity, which is conditioned on several factors, the chief of which are temperature and chemical constitution. As the temperature of the main magma chamber falls (for several obvious reasons), the body passes through a stage where differentiation of the magma is specially liable to take place. That magma may be either the primary basalt or a syntectic. In either case gravity causes the more acid, and generally more alkaline, lighter pole of the differentiation to rise to the surface, where already radiation of heat specially heightens the viscosity. With increase of silica and alkalies at the top of the lava column and decrease of the iron oxides, magnesia, and lime, the viscosity must there rise.

Finally, even in this brief section, some reference should be made to the advisability of distinguishing two chief classes of central eruptions. So far, the feeding magma chamber has been assumed to be a main abyssal injection. Yet it is to be expected that vents may occasionally be opened in the roofs of laccoliths, thick sheets, and other satellitic injections, which have lost thermal and hydrostatic connection with their own parent abyssal injections. For convenience, central vents which are fed directly from the main injections, may be called 'principal'; those fed from satellitic chambers may be called 'subordinate.'

Living and extinct vents, probably belonging to the 'subordinate' class will be described in the forthcoming publication on the nature of volcanic action. That paper will present grounds for the belief that Kilauea in Hawaii is a gas-fluxed hole in the roof of a still-fluid laccolith, while its neighbour, Mokuaweoweo (the main vent of Mauna Loa) is a 'principal' volcano. Branco has concluded that the 127 volcanic 'embryos' of Suabia were vents from a large laccolithic mass of late Tertiary age. Similarly, many of the Scottish necks, made famous by Geikie's monographs, seem to represent late-Paleozoic outbursts of gas from thick sheets (sills and flat laccoliths).

Some of the difficulties of volcanic theory fall away as soon as the distinction between the two kinds of central vents is clearly made. It helps us to understand: the short lives of many volcanoes; the lack of lava flows at many of them; the independent activity of neighbouring vents; the chemical dissimilarity of the lavas from neighbouring vents (each satellitic chamber pursuing its independent chemical evolution along the lines of assimilation and differentiation); the quite common clustering of many small vents in a region which shows no trace or but few traces of alignment among its volcanoes; and the frequent evidence of surface deformation in such regions. The evidences from the existence of 'subordinate' volcanoes are largely indirect but they are numerous, and, taken together, they form a combination of no mean strength.

Gathering all the threads of the argument just presented in skeleton outline, we find them converging to one leading conclusion. The principle of abyssal injection—intrusion of the substratum basalt along mechanically opened fissures in the Earth's acid shell—seems to explain the essential facts of vulcanism. The writer believes, in fact, that this fundamental postulate is as necessary to sound theory in vulcanology as it is in purely plutonic geology.

CHAPTER XXV.

CLASSIFICATION OF IGNEOUS INTRUSIVE BODIES.

Introduction.

In 1905 the writer published a paper on the classification of intrusive bodies, a problem which had already been forced upon his attention during the Boundary survey.* Since that date some discussion of the subject has taken place, especially by Harker, and certain new types may be added to the first classification. In the present chapter the matter of the 1905 paper is summarized, with the inclusion of many of its paragraphs, and some additional considerations will be offered.

Principles of Classification.

A review of the definitions given by the leading authorities on this subject shows that each definition has been based on one or more primary features of igneous intrusions, namely:

(*a*) The method of intrusion.

(*b*) The relation of the body to pre-intrusion structures in the invaded formation.

(*c*) The form of the body.

(*d*) The size of the body.

(*e*) The attitude of the body with reference to the horizontal plane.

For a given body the method of intrusion is the most important criterion that could be used in classification. If it might be determined in every detail just how the igneous mass reached its present position, the form of the body and its relation to structural planes in the country-rock would therewith be known. A genetic, and therefore natural, classification should thus be founded on the method of intrusion. In the present state of geological science it is, however, impossible to apply this fundamental principle throughout the established list of intrusive bodies.

The greater number of recognized types are those of bodies of magma which is exotic except for a small, variable proportion of it due to contact fusion. In each of these cases the magma has come into its chamber through channels which have fed the growing body from larger, deeper-lying, generally invisible reservoirs. The chamber is due to a parting of the country-rock into which the magma is *injected.* An injected body is thus one which is entirely inclosed

* Journal of Geology, Vol. 13, 1905, p. 485.

within the invaded formations, except along the relatively narrow openings to the chamber where the latter has been in communication with the feeding reservoir.

On the other hand, stocks, bosses, and batholiths never show a true floor. They appear to communicate directly with their respective magma reservoirs. Each of these bodies shows field relations suggesting that it is a *part* of its magma reservoir. The communication with the magmatic interior of the earth is not established by narrow openings, but by a huge, downwardly enlarging opening through the country-rock. In relation to the invaded formations a stock, boss, or batholith is intrusive, but is *subjacent* rather than injected.

How a magma reservoir is enlarged by the volume represented in the amount of intrusion signalized on the contacts of stock or batholith is a matter permitting as yet of no absolute certainty. In separating intrusive bodies into two primary divisions, one including all injected bodies, the other including subjacent bodies, a classification will do good service in emphasizing the need of further investigation into the mechanics of intrusion.

So far as the method of intrusion is concerned, therefore, stocks, bosses, and batholiths belong to a primary division of intrusive bodies which may be defined as not demonstrably due to injection. The principle is negative; it leaves the method of intrusion unstated, but it brings into clear relief a principal contrast subsisting between the greatest of intrusions, on the one hand, and dikes, sheets, laccoliths, etc., on the other.

The other principles of classification—viz., (*b*), (*c*), (*d*), and (*e*)—are applied in the classification now to be presented in a manner sufficiently obvious to need no discussion. Principle (*e*) is less fundamental than the others, excepting (*d*), and is recognized as appearing only occasionally in the scheme; the major diameters of true laccoliths tend to horizontality; the principal axis of a bysmalith, neck, stock, boss, or batholith is characteristically vertical.

It is obvious that transitional forms are to be expected among the related types of the classification. These forms are not mentioned in the table, which would thus become overburdened. Magmatic differentiation within dikes, sills, and stocks has often produced varietal types of these bodies, but the process has occurred too irregularly to permit of its furnishing a convenient criterion for the general classification.

Injected Bodies.

Dike.—Most geologists are agreed that dikes in stratified formations are bodies always cross-cutting the bedding planes. Many geologists agree that the angle of dip is immaterial. All agree as to the criterion of form, namely, that of a fissure-filling narrow in proportion to its length and bounded by parallel or nearly parallel walls of country-rock.

When stratification and cleavage or schistosity are not coincident, such an intrusive body is generally called a dike, even though it follows the planes of cleavage or schistosity. This usage will be adopted in the classification to be proposed.

Multiple dikes are compound intrusions of dike form, due to successive injections of homogeneous material on the same fissure.*

Composite dikes are compound intrusions of dike form, due to successive injections of different materials into the same fissure.† Judd recognized a second class of composite dikes as those 'in which a differentiation has gone on in the material that has filled the dike.' These may be distinguished as 'differentiated dikes.' The nomenclature given in the above definitions brings out the analogy with 'multiple' and 'composite' sills and laccoliths—types already well named and established.

A dike network is a reticulate group of dikes simultaneously injected. For illustration see Bulletin No. 209, U. S. Geological Survey, 1903, section on Plate 7.

In the preliminary paper on the classification of igneous masses a place was accorded to 'intrusive veins' and 'contemporaneous veins,' as defined in Geikie's Text-book of Geology. Later discussion with friends, particularly Professors R. W. Brock and Joseph Barrell, has led the writer to exclude these terms from the adopted classification. Messrs. Brock and Barrell agree that it would be better to restrict the name 'vein' to a mass of material crystallized from passing solutions; their point seems to be well taken.

Apophyses or tongues are dikes which, either directly or by inference from field relations, can be traced to larger intrusive bodies as the source of magmatic supply.

INTRUSIVE SHEET.—This familiar expression has generally been defined as equivalent in meaning to 'sill.' It may well be extended to cover the case of an igneous layer injected on a plane of unconformity in stratified formations, when the igneous layer is thus sensibly parallel to the bedding planes of one of the stratified formations. This type, for lack of a better term, may be called an *interformational sheet*. For illustration of such a sheet on a colossal scale, see 'Map of Northern Nickel Range,' Sudbury District, Ontario, by A. P. Coleman.

A *sill* is a sheet of igneous material which has been injected into a sedimentary series and has solidified there, so as to appear more or less regularly intercalated between the strata. (A. Geikie).

A *multiple sill* is a compound intrusion of sill form and relations, and is the result of successive injections of one kind of magma along a bedding plane in a stratified formation.

A *composite sill* is a compound intrusion of sill form and relations, and is the result of successive injections of more than one kind of magma along a bedding plane in a stratified formation. (See Fig. 25, p. 396.)

LACCOLITH.—Those who have made actual researches among laccoliths, and have preserved the term 'laccolith' with the original meaning of Gilbert's

* Geikie, Text-book of Geology, Vol. 2, p. 746. For illustrations, see Harker, Tertiary Igneous Rocks of Skye, pp. 296-304; A. Geikie, Ancient Volcanoes, Vol. 2, p. 417.

† J. W. Judd, Quarterly Journal of the Geological Society, London, Vol. 49, 1893, p. 536; A. Harker, Tertiary Igneous Rocks of Skye ('Memoirs of the Geological Survey of Great Britain,' 1904), p. 197.

broader definition, are agreed on the following characteristics: (*a*) Whatever the origin of the force involved, a laccolith is always *injected.* (*b*) A laccolith is always in sill relation to the invaded, stratified, formation; that is, the injection has, in the main, followed a bedding plane; but, like sills, laccoliths often locally break across the bedding. (*c*) A laccolith has the shape of a plano-convex lens flattened in the plane of bedding of the invaded formation. The lens may be symmetric or asymmetric in profile; circular, oval, or irregular in ground plan. (*d*) There are all transitions between sills and laccoliths.

For many illustrations of simple symmetric and asymmetric laccoliths, see the writings of Gilbert, Cross, Weed and Pirsson, and Jaggar.

A *multiple laccolith* may be conceived, the name being formed on the analogy of 'multiple dike' and 'multiple sill.' It would differ from a compound laccolith only in the fact that the deformation of the strata, while again similar in character to that produced during the intrusion of a simple laccolith, has been due to distinctly successive injections of the same kind of magma. This case has not yet been described as actually occurring in nature.

Harker* has noted the occurrence of '*composite laccoliths*' in the island of Skye. Through the chemical contrasts of their successively injected parts, they are distinguished from multiple laccoliths.

Weed and Pirsson† have described as a laccolith a great, lenticular mass of porphyry injected along a surface of unconformity, namely, that between pre-Cambrian crystalline schists and a sedimentary Cambrian formation. Such a type is again aberrant from Gilbert's types, but should certainly be classed among the laccoliths; the writer proposes the not altogether satisfactory name '*interformational laccolith*' for this case. (Compare a similar section of an occurrence in the Black Hills of South Dakota, published in the *Annals of the New York Academy of Science,* Vol. 12, 1899, p. 212.)

PHACOLITH.—Harker has recently proposed 'phacolite' as a new name for a type among the 'concordant intrusions.' He writes:—

> 'In the ideal case of a system of undulatory folds there is increased pressure and compression in the middle limbs of the folds, but in the crests and troughs a relief of pressure and a certain tendency to opening of the bedding-surfaces. A concurrent influx of molten magma will therefore find its way along the crests and troughs of the wave-like folds. Intrusive bodies corresponding more or less closely with this ideal case are common in folded districts. Since some distinctive name seems to be needed, we may call them *phacolites.* The name laccolith has often been extended to include such bodies, but this is to confuse together two things radically different. The intrusions now considered are not, like true laccoliths, the cause of the attendant folding, but rather a consequence of it. The situation, habit, magnitude, and form of the phacolite are all determined by the circumstances of the folding itself. In cross-section it has not the plano-

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* A. Harker, Tertiary Igneous Rocks of Skye, 1904, p. 209.
† Journal of Geology, Vol. 4, 1896, p. 402.

convex shape of the laccolith, but presents typically a meniscus, or sometimes a doubly convex form. Except where the folding has the character of a dome, a phacolite does not show the nearly circular ground-plan of a laccolith, but has a long diameter in the direction of the axes of folding. As regards the mechanical conditions of its injection, the phacolite resembles rather the small subsidiary intrusions which sometimes accompany a laccolith, and are consequences of the sharp flexure caused by the primary intrusion.'*

It may be noted that 'phacolith' is a preferable spelling because it is of the same form as the internationally spelled 'laccolith,' 'batholith,' etc., all of which have come directly from the Greek, and should therefore have the 'lith' termination. Moreover, the word 'phacolite' is already pre-empted by mineralogy as the name of a zeolite.

Some of the laccoliths as understood and described by Cross, Jaggar, and others belong in the class of 'phacoliths.'

BYSMALITH.—Allied to 'plugs' in Russell's sense is the 'bysmalith' of Iddings, described as an injected body filling a 'more or less circular cone or cylinder of strata, having the form of a plug, which might be driven out at the surface of the earth, or might terminate in a dome of strata resembling the dome over a laccolith. The downward termination of the original type bysmalith (Mt. Holmes) is found in a hypothetical Archean floor on which the porphyry of the bysmalith rests. Such a body may be regarded as a laccolith which lifted its cover along circumferential faults in the roof, rather than by the mere flexing of its strata.†

VOLCANIC NECK.—The solid-lava filling of a volcanic vent is evidently intrusive with reference to the formations traversed by the lava, whether those formations are composed of non-volcanic rocks or of agglomerate or tuff which has been pierced by thoroughly molten lava on its way to the surface.

CHONOLITH.—There remains for distinction a class of injected igneous bodies which are not included in any of the above-mentioned categories. In the dislocation of rock formations such as is brought about during mountain-building, actual or potential cavities are formed within the earth's crust. These are commonly filled with igneous magma squeezed into the individual cavity from below, from the side, or, it may be, from above. Dikes, sills, and bodies of laccolithic form (though not strictly of the laccolithic mode of intrusion, as designated by Gilbert) may thus originate. Yet very often the shape of the intruded mass is so irregular, and its relations to the invaded formations so complicated, that the body cannot be classified in any of the divisions so far named. Again, irregular injected bodies of a similarly indefinite variety or form are due to the active crowding-aside and mashing of the country-rock which is forced asunder by the magma under pressure. Or, thirdly,

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* A. Harker, The Natural History of the Igneous Rocks, New York, 1909, p. 77.
† J. P. Iddings, Monograph 32, Part 2, U.S. Geol. Survey, 1899, p. 16.

such bodies may be due to a combination of the two primary causes—orogenic stress opening cavities, and hydrostatic or other pressure emanating from the magma itself and widening the cavities.

No generally accepted name has yet been proposed for such irregular intrusions. 'Laccolith' cannot be used, since that term denotes a definite form, and also implies a special mode of intrusion different from that here conceived. The writer has not been able to find a simple English word for the purpose, and suggests a name formed from the Greek on the analogy of 'laccolith,' 'bysmalith,' and 'batholith.' It is 'chonolith' derived from χωνος, a mould used in the casting of metal, and λιθος, a stone. The magma of a 'chonolith' fills its chamber after the manner of a metal casting filling the mould. Like a casting, the 'chonolith' may have any shape.

A 'chonolith' may be thus defined: an igneous body (*a*) *injected* into dislocated rock of any kind, stratified or not; (*b*) of shape and relations irregular, in the sense that they are not those of a true dike, vein, sheet, laccolith, bysmalith, or neck; and (*c*) composed of magma either passively squeezed into a subterranean orogenic chamber or actively forcing apart the country-rocks.

The chamber of a 'chonolith' may be enlarged to a subordinate degree by contact fusion on the walls, or by magmatic 'stoping.'

Examples of 'chonoliths' are described on pages 368, 401, 418, and 499, and many bodies of this class have been mapped and sectioned in works dealing with the western Cordillera of the United States.

It may be specially noted that this new term may be useful in suggesting the probable nature of an injected body in the case where its whole form is not certainly known. The context should then, of course, indicate that the author using the term has in mind only a probability and is making, as it were, simply a report of progress in the description of that particular body.

ETHMOLITH.—The *ethmolith* (funnel-shaped stone) of Solomon is one of the many conceivable species of chonoliths. He considers that the tonalite mass of Adamello is an example. At the present erosion-surface the surrounding strata dip towards the tonalite on every side and he concludes that they converge, underground, so as to cut off the igneous body except for the narrow dike, or sill-feeder of the injection. On the other hand the body is supposed to have enlarged to its rather flat roof, the whole form simulating a funnel. If the field diagnosis be correct, the tonalite is to be regarded as an injected mass, partly cross-cutting the strata and thus has chonolithic relations.*

SUBJACENT BODIES.

BOSS.—A. Geikie † defines bosses as:

'Masses of intrusive rock which form at the surface rounded, craggy, or variously shaped eminences, having a circular, elliptical or irregular ground plan, and descending into the earth with vertical or steeply inclined

* Cf. W. Salomon, Sitzungsberichte der königlichen preussischen Akademie der Wissenschaften, Phys.-Math. Classe, Vol. 14, 1903, p. 310.
† Ancient Volcanoes of Great Britain, Vol. I, 1897, p. 88.

sides. Sometimes they are seen to have pushed the surrounding rocks aside. In other places they seem to occupy the place of these rocks through which, as it were, an opening has been punched for the reception of the intrusive material. . . . In true bosses, unlike sills or laccolites, we do not get to any bottom on which the eruptive material rests.'

He makes 'stock' and 'boss' synonymous.

In English and German-speaking countries 'boss' and 'stock' are almost invariably regarded as synonymous, but the latter term has much the greater vogue. The general connotation of the word 'boss' seems to warrant the restriction of its meaning so as to include only those stocks which have circular or subcircular ground plans on the surface of exposure. The word has been used to denote intrusions of the sort up to all diameters from a few hundred feet to several miles.

Bosses are '*simple*' when composed of material intruded in but one period; they are '*multiple*' or '*composite*' when composed of material intruded at two or more distinct periods of irruption. The distinction between the latter types is similar to that between 'multiple' and 'composite' stocks.

STOCK.—Prevailing usage has fixed the meaning of 'stock' as essentially equivalent to Geikie's definition of 'boss.' A stock is an intrusive body but is not as clearly *injected* as is the case with a dike, sill, or laccolith. A stock more or less conspicuously cuts across the structures of the invaded formations; its contacts are, in general, either vertical or highly inclined; its shape is irregular and not determined by planes of bedding or other structures in the country-rocks. It has no visible floor.

Simple stocks are composed of material intruded in one period of irruption.

A *multiple stock* is composed of material demonstrably intruded in two or more periods of irruption, the material having been derived from the same kind of magma.

A *composite stock* is composed of materials demonstrably intruded in two or more periods of irruption, the materials having been originally derived from two or more kinds of magma.

Magmatic differentiation or other influences may render heterogeneous the material composing a simple stock, or each member of either a multiple or a composite stock.

BATHOLITH.—Suess has finally stated the definition of 'batholith' in terms of a theory of intrusion which is at present in discussion. His definition may be freely translated thus: 'A batholith is a stock-shaped or shield-shaped mass intruded as the result of fusion of older formations (orig. *Durchschmelzungsmasse*). On the removal of its rock-cover and on continued denudation, this mass either holds its diameter or grows broader to unknown depths (orig. *bis in die ewige Teufe*.* The name was invented to describe those largest of all intrusions, generally granitic, which are characteristically found in great mountain ranges; including, thus, 'central granites,' 'intrusive mountain-cores,' and 'Fuss-

* Sitzungsberichte der Wiener Akademie, Vol. 104, 1895, p. 52.

granite.' The name has since been commonly used for bodies of intrusive rock with the general characteristics of stocks, but of much larger size than is generally attributed to stocks or bosses. This latter use is, moreover, rarely associated directly with any particular theory of intrusion. There is pressing need for such a term signifying these large bodies, and one that will not commit the field worker to any theory of origins. The later use of the term 'batholith' is therefore to be commended, as it renders that term safe in actual field descriptions where these cannot be accompanied with certain proofs that the *Durchschmelzung* theory is there applicable. In the proposed classification of intrusives the term 'batholith' will have the meaning just noted.

A *simple batholith* is one composed of material intruded in one period of intrusion.

A *multiple batholith* is one composed of material demonstrably intruded in two or more periods of irruption, the material having been derived from the same kind of magma.

A *composite batholith* is one composed of materials demonstrably intruded in two or more periods of irruption, the materials being originally derived from two or more kinds of magma.

A multiple or composite batholith may thus be in part made up of stocks.

Magmatic differentiation or other influences may render heterogeneous the material composing a simple batholith; or each member of a multiple or a composite batholith.

No author has attempted to fix a lower limit to the areal dimensions of a batholith. Since there is no certain distinction either in form or relations between stocks and batholiths, an arbitrary limit may be set between the two on the score of areal extent. In the 1905 paper it was proposed that the upper limit in the size of stocks be placed at 200 square kilometres. A further study of the literature has made it seem advisable, in order to conform to actual usage, to make the limit no higher than 100 square kilometres. Any mass with the stock relations, but of greater area than 100 square kilometres, is, accordingly, a batholith.

Proposed Classification.

The following table gives the proposed classification, as slightly enlarged from that in the 1905 paper:—

A.—Injected masses.

I. *Concordant injections (injected along bedding planes).*

1. Intrusive sheets, homogeneous and differentiated.
   (*a*) Sills.
      (1) Simple.
      (2) Multiple.
      (3) Composite.
   (*b*) Interformational sheets.

2. Laccoliths, homogeneous and differentiated.
    (1) Simple.
        Symmetric.
        Asymmetric.
    (2) Multiple.
    (3) Composite.
    (4) Interformational.
3. Phacoliths.

II. *Discordant injections (injected across bedding planes).*

1. Dikes, homogeneous and differentiated.
    (1) Simple.
    (2) Multiple.
    (3) Composite.
2. Apophyses or tongues.
3. Bysmaliths.
4. Necks.
5. Chonoliths.
    Ethmoliths.

B.—Subjacent masses.

1. Stocks and bosses, homogeneous and differentiated.
    (1) Simple.
    (2) Multiple.
    (3) Composite.
2. Batholiths, homogeneous and differentiated.
    (1) Simple.
    (2) Multiple.
    (3) Composite.

The classification can lay no claim to completeness, but it suffices to point to the real crux of the present situation in igneous geology. In spite of some uncertainties regarding some types the modes of intrusion for the injected masses are fairly well understood. It is quite different with the vastly larger, subjacent masses, from which many of the bodies of the first group have been derived, and of which they are to be regarded as satellites. The problem of the batholithic form and relations is, therefore, the difficult prelude to the complete understanding of the injected bodies whether considered with respect to petrogeny or to the dynamics of their injection. If the batholithic problem is solved we shall have essential facts regarding the origin of magmas. For this reason a somewhat detailed discussion of the methods of batholithic intrusion may well anticipate the study of magmatic differentiation. The discussion will be based on the idea of a primary acid earth-shell and a basaltic substratum. It will be seen that a multitude of field and laboratory observations agree in supporting this conception as well as the hypothesis of abyssal injection. The conclusion will be reached that batholiths are the more or less chemically-modified *tops* of abyssally injected bodies of basalt. The smaller injected masses of Group *A* in the classification are explained as, either direct offshoots from the abyssal basaltic injections, or as satellites from the secondary magma developed in batholithic chambers. In brief, batholiths appear to represent abyssally injected bodies of such size and original temperature as to be capable of assimilating large volumes of the primary acid shell and, on occasion, notable amounts of the overlying sediments.

CHAPTER XXVI.

MECHANISM OF BATHOLITHIC INTRUSION.

The facts to be explained by a final theory of batholiths fall into three classes: field relations, time relations, and chemical relations. At the risk of repeating statements made in preceding chapters as well as many of those published by other writers, a summary of the leading pertinent facts may well anticipate the theoretical discussion. It will be understood that stocks and bosses are regarded as only small batholiths or as parts of batholiths, and in many cases will not be specially named.

FIELD RELATIONS.

There is general agreement that batholiths are to be found only in, or on the immediate borders of, mountain-built regions. This rule is so general that it may be called a law. Almost if not quite as general is the rule that batholithic intrusion to observed levels in a mountain-range, follows the climax of an orogenic paroxysm; though flow-structures and gneissic structure may be induced in the batholith in the closing, weaker stage of the crustal movement. The gneissic structure may be difficult to distinguish from that due to a later, independent period of crushing. Abundant examples of the two rules are noted in the summary geological histories of the Selkirk, Columbia, and Cascade ranges. The Rykert batholith is the only one on the Forty-ninth Parallel which seems to have a well developed primary flow-structure.

No one has ever seen the bottom of stock or batholith. Owing to the limited amount of possible upheaval of the earth's crust above baselevel, erosion has probably never been able to penetrate more than six miles into these masses and, in general, penetrates less than three miles. In each case, therefore, the observer walks on a surface near the top of the body. Sometimes erosion has not yet uncovered such granitic masses, whose presence is detected by the heavy contact metamorphism so characteristic of batholiths. More often the roof is partly destroyed, leaving broad belts of metamorphosed roof rock about the cupola-like intrusive, and roof-pendants within it. A fine example of a partially uncovered stock is that at the Dewdney trail on the summit of the Selkirks (see page 299). Perhaps the majority of exposed batholiths have lost their roofs so far that only small areas of the pendants remain, while the metamorphic aureole has the narrowness appropriate to the wall of a batholith. Not even one roof-pendant is known in the Coryell batholith of the Columbia range. (See page 358 and map sheet.)

With deep erosion and destruction of the roof the molar (main) contact has typically an elliptical ground plan, though it is often irregular. Disregarding the apophyses, the molar-contact line is usually a flowing one and does not show sharp angles. Whether elliptical or irregular in ground plan, the longer axes of batholiths characteristically run with the average local trends of the respective mountain-axes developed in the orogenic period immediately preceding the intrusions. The batholithic axes may have indefinite relations to axes of earlier and later crustal deformation. In the Cordillera the alignment of the Mesozoic and Tertiary batholiths parallel to the main axis of the chain is evident in the geological maps of both Canada and the United States.

The downward enlargement of stocks and batholiths to the maximum depths exposed by erosion has already been sufficiently emphasized and illustrated in the description of the Cascade mountains (pages 428 and 494). Many additional examples are figured in Lepsius' 'Geologie von Deutschland,' and in other works.

The lower limit for the area of exposed batholiths has been arbitrarily fixed at 100 square kilometres, but in very many cases, stocks or bosses are with considerable certainty to be regarded as merely cupola offshoots of large batholithic masses, which by continued erosion might be exposed. Indeed, it may be true that every stock and boss is but part of a batholith. The maximum size of pre-Cambrian batholiths may be greater than that of any later one. The batholith of the British Columbia-Alaska Coast range is probably the most extensive of the known post-Cambrian intrusive masses. It is mapped as about 1,200 miles long and over 75 miles in average width. One must suspect that this immense terrane is a composite of several, perhaps many, batholiths of different ages.

That the molar contact of the average stock or batholith cuts across pre-intrusion structures in the country-rock is another obvious fact. This cross-cutting relation is found not only where strong gneisses, schists, and massive rocks compose the country-rock, as at Mount Ascutney, Vermont;* it is as clearly shown where the Castle Peak stock truncates the soft shales of the Hozomeen range (Page 495.) A multitude of such parallels proves that the shapes of stocks and batholiths are not controlled essentially by variations in the strength of the invaded formations; we have seen that laccoliths are just as regularly located in zones of shales or other rocks more easily split than their respective neighbours.

The cross-cutting relation of batholiths is sometimes masked, though never annulled, by the development of peripheral schistosity or cleavage parallel to the molar (main) contacts. The best illustration in the Boundary belt is found in the southern contact of the Bayonne batholith, Selkirk range (See map sheet and page 292). Other well known examples occur in the Sierra Nevada,† the Black Hills,‡ and the Rainy Lake region of Ontario.§

As a rule, batholiths do not develop peripheral cleavage or schistosity in marked degree nor cause important changes in the regional strike of the invaded formations. The large scale, detailed maps of the European surveys are crowded

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* R. A. Daly, Bulletin 209, U.S. Geol. Survey, 1903.
† H. W. Turner, 17th Ann. Rep. U.S. Geol. Survey, Pt. I, 1895-6, p. 555.
‡ C. R. Van Hise, 16th Ann. Rep., U.S. Geol. Survey, Pt. I, 1894-5, pp. 637 and 815.
§ A. C. Lawson, Ann. Rep., Geol. and Nat. Hist. Survey, Canada, 1887, Part F, map.

with illustrations of this fundamental fact. Barrois' maps of Britanny are eloquent for all the cases. Numerous examples may be found in the Boundary map sheets. (See also pages 292, 299, 302, 426-30, 465, and 495-99.)

It is a truism that batholiths generally have wider aureoles of contact metamorphism than laccoliths, or than other injected bodies. In apparently all cases, as we have noted, the intensity of the metamorphism is greatest at the roof, less at the wall, of both stocks and batholiths. The explanation is almost surely found in the tendency of the volatile constituents of the magma to collect at the roof. Since stocks are generally cupola-like masses at batholithic roofs we can readily understand the fact that the aureoles of heavy metamorphism about stocks may be wider than the wall-contact aureoles of even very large batholiths. But it remains true that the degree of contact metamorphism exhibited in batholithic aureoles is often much less than that often shown at dikes and sheets, *if account be taken of the volumes of magma involved.*

This fact becomes understood by assuming that these injected bodies were, at the time of intrusion, much hotter than the average batholithic magma was when its *visible* molar contact was established. The mere fact that dike and sheet magma could penetrate miles along relatively narrow fissures in the earth's crust speaks for some amount of superheat. The presence of quartz instead of tridymite (inversion point about 800° C.) in the vast majority of batholiths proves a very low temperature for their magmas as these crystallized at the visible contacts. The low temperature at that stage is likewise proved by the evidence of enormous viscosity in the magma during the crystallizing period. Such viscosity must be assumed because of the suspension of foreign blocks of rock which is much denser than the crystallized intrusive and, *a fortiori*, than the magma that crystallized. The facts of the field thus lead the observer directly to question the statement that the existing batholithic contacts were established at the time of initial intrusion. If the batholiths are due simply to injection, like dikes, sheets, and laccoliths, why should they be so greatly super-cooled, while the much smaller bodies are as often superheated? The whole matter becomes clear if it be assumed that the initial temperature of a batholith was as high as that of its hottest satellite, and that during the long period of cooling the magma of the main chamber incorporated masses of the country-rock. In this way *new* contacts were established in succession, and the last one, with a *relatively* narrow contact aureole, was established in the feeble, supercooled condition of the magma just before solidification. This theoretical deduction is so patent that it is ranked alongside of the 'facts' of field relations.

Among the commonest phenomena associated with the contact zones of plutonic, igneous rock bodies(bosses, stocks and batholiths) is that of extensive shattering and disruption of the invaded formations along the contacts. A host of memoirs on exotic granite, syenite, diorite, gabbro, and other deep-seated rock masses contain references to this particular phenomenon. It consists, in its ideal development, of the appearance of two concentric belts of mixed rock occurring between the homogeneous main body of igneous material and the encircling country-rock unaffected by any serious mechanical disturbance due to the intrusion. Both belts lie parallel to the average line of contact between the intrusive and the country-rock.

The belt more remote from the intrusive body is generally much the broader of the two and consists of country-rock intersected by more or less numerous apophyses from the main igneous mass.

The second belt is composed of igneous rock enclosing blocks of the country-rock. As the apophyses, breaking the continuity of the invaded formation, vary enormously in number within the outer belt, so the blocks, breaking the continuity of the igneous body, show the greatest variation in abundance. This belt of inclusions varies in width from a few feet to two miles or more. The blocks, unless very close together and possessing thoroughly massive structure themselves, usually show clear evidence of having been shifted out of their former relative positions in the invaded formation, so that their original orientation is completely lost. There are transitions to the outer belt through the gradual increase in the number of blocks left undisturbed from their original orientation; and there is, of course, no easily fixed boundary between the belt of inclusions and the main intrusive body in which country-rock inclusions are normally absent or very rare. The inner boundary of the belt of inclusions is often difficult to determine in the case of stock or batholith so exposed to view by denudation as to furnish a land surface close to the former roof of the magma chamber.

Whatever be the causes of the disruption of blocks now found in the belt of inclusions, those causes are directly connected with the intrusive body itself and are thus not external. The belt is, for example, not due in the normal case to the injection of magma into rock coarsely brecciated by regional dynamic movements in the earth's crust. Movements of that sort tend generally to brecciate rock along straight or open-curve lines and would not necessarily follow the complex, sinuous, closed-curve line of contact such as belongs to a plutonic body. There is certainly, on the other hand, a genetic relation between the belt of inclusions and the replacement of the country-rock by great bodies of intruded magma almost or quite free of foreign fragments. Many authors speak of the inclusions as having been 'torn off' or 'carried up' by the ascending magma, without, however, showing the possibility of such a process when correlated with the apparently demonstrated liquidity of plutonic magmas.

Some of the blocks within the belt of inclusions have unquestionably been floated out or sunk from the molar contact after those portions of the country-rock have been completely surrounded by magma of the main body and of anastomosing apophyses. But there are reasons for concluding that apophyses of an abundance matching the countless inclusions of many internal contact-belts, were not formed simply by reason of hydrostatic pressure forcing magma into original cracks or fissures in the country-rock. The conditions reigning at the contact imply the exhibition of a different source of energy—one which many geologists have incidentally credited with the shattering effect.*

* These and many following paragraphs are adapted from the writer's papers on 'The Mechanics of Igneous Intrusion,' American Jour. Science, Vols. 15 and 16, 1903, and Vol. 26, 1908.

McConnell long ago noted the remarkable shatter-belt bounding the Trail batholith in the Columbia River valley. (See Sheet 8). Less conspicuous cases occur in many other parts of the Boundary section. In eastern Massachusetts these belts sometimes cover so many square miles together that we must believe that main batholithic masses lie beneath, at but moderate depths. The best published example of a small granite batholith mapped with the distinct purpose of illustrating a shatter-zone is doubtless that due to the labours of Coste and White in the Madoc-Marmora Mining District of Ontario.† A reduced copy of this map was published in Volume 16 of the American Journal of Science (1903, page 118).

TIME RELATIONS.

The rule that batholithic and stock intrusions to observed levels always follow the climax of orogenic movements is recognized by all geologists who have had wide experience in the study of granites. This systematic time relation seems to hold, with some possible exceptions, from the latest Tertiary back to the date of the youngest pre-Cambrian granites cutting bedded rocks. The rule may not apply to many of the pre-Cambrian batholiths, which seem to have been under severe orogenic pressure during their actual intrusion. Moreover, the greater number of mapped pre-Cambrian batholiths do not show the same rigour of alignment parallel to distinct orogenic axes as that characterizing the later batholiths. The early pre-Cambrian conditions of intrusion may, therefore, have differed in certain essential ways from the ruling post-Cambrian conditions.

CHEMICAL RELATIONS.

Most batholiths are granitic in composition. Some of the largest are composed of granodiorite or quartz diorite. A few small batholiths are syenitic. The huge anorthosite masses of eastern Canada, New York State, and Scandinavia may have true batholithic form and field relations, but this is not certain. No large body of anorthosite of date later than the Silurian is known, while the majority are of pre-Cambrian dates. Stocks have much greater range of composition, including the series from true diorite to aplitic granite, various types of syenite, nephelite syenite, monzonite, etc.

It is noteworthy that no undoubted batholiths, which are chemically equivalent to normal basalt, seem ever to have been mapped. That effusive magma which occurs in the largest quantity, and with such wonderful uniformity of chemical constitution, is not directly represented among the larger subjacent bodies. Even small gabbro stocks are extremely rare, if, indeed, they exist.

Within the writer's knowledge, no large batholith is known in a petrographic province which does not carry dikes or other injected masses of basaltic composition (diabase, porphyrite, gabbro, or basalt).

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† Geol. and Nat. Hist. Surv. of Canada, Special sheet; ½ mile to 1 inch, published without text. 1886.

The homogeneity of the average batholith in its visible portion is worthy of special note. The stress continually being laid on evidences of differentiation (basified contact-belts, segregations, etc.,) is in danger of obscuring this principal fact. The homogeneity of one of these large masses, when viewed in true scale, is comparable to that in aqueous salt-solutions in laboratory vessels. The production of this even distribution of oxides must involve vast periods of time and vast stores of heat to keep the magma fluid for the distribution.

In general a batholith is markedly different from its country-rocks in chemical composition.

A long list of other chemical relations, which need to be explained by any theory of batholithic intrusion, might here be drawn up, but, to save repetition, their discussion will be transferred to the following theoretical sections on magmatic assimilation and differentiation.

THEORIES OF BATHOLITHIC INTRUSION.

Having briefly reviewed the main facts to be explained, we may now proceed to outline the various theories which have been proposed.

'Laccolithic' Hypothesis.

One school of geologists would extend the laccolithic idea to many, if not most, granitic intrusions. Accordingly, the chambers filled with such igneous masses are interpreted as the products of crustal displacement. The planes of single great faults may, in this way, become the locus of the subterranean eruption of magmas, wedging their way along by hydrostatic or other pressure. The well-known 'failure to match' of the heaved and thrown sides permits of the existence of potential cavities filled with magma during the strong dislocation. Encircling faults leading to the foundering of large blocks of the crust, or to the upward thrust of others, are conceived as affording possible modes of intrusion.* Or, finally, as illustrated in the well-known conclusions of Brögger on the Christiania region, colossal masses of granite have been explained as true, deep-seated laccoliths, parting heavy strata after the manner of the trachyte of the Henry mountains.†

Yet it is clear from a survey of geological literature, that the field evidence for such a view is but negative in the great majority of stocks and batholiths. Most of them are not true laccoliths, since they characteristically occur in regions of great structural complexity, where igneous contacts have none but the most remote sympathy with the structural planes of any one bedded series. Many are much too large and irregular in form to be explained as the result of single faults or single zones of faulting; and the imagined intersecting faults of the 'bysmalith' or of the submerged graben-block have been generally sought for in vain about those greatest of all granitic massifs. For the latter no other

* W. C. Brögger, Die Eruptivgesteine des Kristianiagebietes, Vol. 2, 1895, p. 148; J. P. Iddings, U.S. Geol. Survey, Monograph, 32, Part 2, 1899, p. 16.

† W. C. Brögger, op. cit., p. 152.

interpretation seems possible by the theory outlined. On the other hand, every observer who has even a small acquaintance with crystalline terranes of the sort, is now and again struck with the evidences that the granitic magmas represented in his field of study are far from being passive in the hands of the eruptive Titan. Their general defiance of structure and composition in the invaded formations, the irregular ground-plans, and the huge finger-like projections sent into the country-rocks, which are undisturbed either in dip or strike, are among the familiar phenomena indicating that such magmas actively, aggressively 'made their way in the world' by the irregular removal of the invaded formations. The latter look as if they had been, as it were, corroded on a huge scale.

The 'laccolithic' hypothesis finds no support in the facts already learned concerning the greater intrusive bodies of the Boundary belt. It is, for example, virtually inconceivable that the Okanagan composite batholith could have been developed in its present size and relations by mere injection. If the older rocks parted successively, to admit the huge masses of the Osoyoos, Similkameen, and Cathedral masses, the traces of these scissions must be left, yet none has been discovered. How any one of them could, like a laccolith or like some chonoliths, enter its chamber by lifting its roof without somewhere breaking through to the earth's surface, is a puzzle, to say the least.

Those who so lightly apply this hypothesis have usually neglected to prove, or even discuss, the nature of the structure which, for batholiths, is the equivalent of a weak zone in the Henry Mountains. The typical laccolith was intruded in stratified rock and in an easily-split zone of shale. What is the analogous (sub-horizontal) crustal structure which, on this hypothesis, must be antecedent to the injection of the greater bodies? The granites characteristically appear in the complexly folded terranes which are exceptionally strong. Many large granitic masses, like the Cathedral batholith, (see page 459 and map), have broken through more or less massive plutonics. The laccolithic hypothesis implies the abundant recurrence of a relatively flat plane of weakness a fraction of a mile, or a few miles, below the surface of the mountain ranges. Why it should occur there, or how developed, has never been suggested.

This hypothesis is powerless to explain the field relations of the Castle Peak stock, the stocks of the Selkirk range in the Boundary belt, or many others of the smaller granitic bodies in the belt. These are small enough to admit of rather complete diagnosis, yet in no case is there any ground for the explanation by pure injection. Large or small, batholiths or stocks, the granitic bodies along the Forty-ninth Parallel must be otherwise understood.

'Marginal Assimilation' Hypothesis.

The insufficiency of the pure-injection hypothesis has caused a second school of geologists to emphasize a hypothesis of slow caustic action by magmas that have advanced into the overlying earth-crust by their own energetic solvent action on the walls and roofs. Additional evidence for the truth of this contention is sought in the facts of the internal contacts, at which magmas are sometimes seen to be modified by the incorporation of the country-rock. This second view doubtless appeals the more strongly to the majority of those geologists who have actually to do with granitic bodies in the field. In fact, the impression has prevailed among some of them that the 'laccolithic theory' is as widely held as it is because of its apparent necessity in the prevailing theory of rock differentiation. Yet it must be considered as conclusively proved for the great majority of stocks and batholiths investigated, that analysis has not yet shown that the second or 'assimilation' theory really meets its own crucial test, the chemical and mineralogical blood-relationship between the average intrusive rock and its country-rock along their mutual contact. Currents within the magma would, of course, tend to remove and diffuse products of assimilation from molar contacts; but it is extremely doubtful that they could so completely mask the expected results of the process as is over and over again illustrated in nature. No single fact concerning granite, for example, is more striking than its astonishing homogeneity in contact with argillite, limestone, crystalline schist, or basic igneous formation—a homogeneity that persists, too, from contact to center of the eruptive. In the very common case where the assimilated product is more acid than the original magma, it would tend to rise through the latter, slowly diffusing in the journey. The upper part of the magma basin should, for that reason, become filled with mixed magma more silicious than the original. Heterogeneity, even stronger vertically than horizontally, would be expected in a diorite or gabbro magma cutting crystalline schists, or in a granite magma cutting heavy beds of sandstone or quartzite. True thermal convection currents must, under these conditions, be greatly weakened by the strong differences in density of the original magma and the magma diluted, so to speak, by more silicious material. In the absence, then, of the only kind of current likely to be set up in the process of cooling and mere caustic solution on molar contacts, the diffusion of the diluted magma would take place only with extreme slowness.† Yet, up to the present time, this consequence of considerable vertical heterogeneity under the stated conditions has not been demonstrated in nature. The recorded field discoveries point, on the contrary, to a distinct failure of the known facts to match the deduction from the theory. The few proved instances of endomorphic changes of magmas by assimilation (e.g., the granite of the Pyrenees described by Lacroix) serve, by their conspicuous and exceptional nature, to show that granitic magmas, if they have 'made their own way' at all, have usually done so in some manner different from merely assimilating the invaded formations on molar contacts.

A main feature of the explanation by marginal assimilation is the immense superheat demanded in the magma. If the solution of invaded formations is directly performed by the liquid rock, the available superheat must be speedily exhausted in supplying the latent heat represented in the solution, to say nothing of the loss by conduction through the earth's crust. The latent heat, according to Vogt and others, is at least 20 per cent of the total melting heat in

† Cf. G. F. Becker, Amer. Jour. Sci., Vol. 3, p. 30, 1897.

fluid lava. There is no reason to believe that exothermic reactions are of any moment under the conditions. Since, as we have seen, vertical currents are soon inhibited, the continuance of solution at the roof waits on conduction. Unless we postulate a degree of superheat utterly without parallel in the hottest volcanoes, such as at Kilauea, at Mauna Loa, and at Matavanu, Savaii, the extensive solution implied by this hypothesis is impossible.

The favorite conception of the French geologists, that the necessary solution of the roof rocks has been due to the influence of juvenile gases *(agents mineralisateurs)*, rather than to direct solution in liquid magma, is likewise difficult to accept. Because the specific heat of a gas at low pressures is extremely small as compared with that of rock-matter, we perceive that a quite incredible amount of gas is necessary to liquefy thousands of feet of roof rock by blow-piping, or by its mutual solution with the gas. There is no general physical cause for a return of gas to the depths after it has done its solvent work. It must collect at the batholithic roof either free or dissolved in the syntectic magma. In either case its tension must increase and when the accumulation approaches the limit implied in the hypothesis, the gas pressure must rise far beyond that which the earth's crust could endure. The fact is that volcanic action is not always, nor even generally, the result of batholithic intrusion. We know that the implied crustal catastrophes, indefinitely greater than Krakatoan explosions, have not occurred in post-Cambrian time at least. Juvenile gases may bore the holes at volcanic vents and they have doubtless aided somewhat in the underground solution of rock; but it seems impossible to believe that they are the leading agents in fashioning batholithic chambers, even for the moderate depths exposed by erosion.

The old idea that batholiths are simply geosynclinal sediments which have been fused by the rise of the isogeotherms, has been recently revived by Haug.* Space is lacking for the full discussion of this speculation, nor at this day is it necessary to lay the ghost again. A few remarks will suffice to show its inapplicability to the batholiths on the Forty-ninth Parallel.

The Rocky Mountain geosynclinal is one of the thickest on record. Crustal movements have exposed its lower beds at many points; yet they are *not* fused. The same is true of the basal beds of the Cretaceous geosynclinal of the Hozomeen range and California, each nearly 30,000 feet thick. On the other hand, many batholiths have appeared in deformed geosynclinals of much less thickness. Examples are seen in the Coryell batholith and that which has so many satellites in the Boundary Creek district of the Columbia range.

Again, the speculation may be dismissed because of its manifest failure to provide the necessary heat supply. The lowering of the 'fusion-point' of average sediments by admixture of the 'agents minéralisateurs' can hardly be supposed to give a magmatic temperature below 500°C for a batholith. Yet no known geosynclinal is thick enough to have assumed this temperature in its lower beds through the rise of the isogeotherms. Haug does not, therefore, essentially improve the speculation by an appeal to the rather mystical 'agents

* E. Haug, Traité de Géologie, tome 1, Paris, 1907, p. 188.

minéralisateurs.' Moreover, every batholith occurring in the Forty-ninth Parallel section is clearly *exotic* with respect to the surrounding formations. This exotic relation applies not only to satellitic offshoots but also to the main bodies exposed. In this respect, as in many others not here mentioned, the combined influence of mineralizing agents and of the basal warming of geo-synclinals cannot account for the granitic masses of the Boundary belt.

Hypothesis of Magmatic Stoping.

Summary.—The general statement of this hypothesis may be conveniently quoted from the third of the writer's papers on the 'Mechanics of Igneous Intrusion.'*

1. Each acid, batholithic magma has reached its present position in the earth's crust largely through the successive engulfment of suites of blocks broken out of the roof and walls of the batholith.

2. The blocks (xenoliths) are completely immersed in the magma, partly through the confluence of apophyses which have been injected on joints and other planes of weakness in the country-rock; more often the blocks represent the effect of shattering, due to the obviously unequal heating of the solid rock at magmatic contacts.

3. The sunken blocks must be dissolved in the depths of the original fluid, magmatic body, with the formation of a syntectic, secondary magma.

4. The visible rock of each granite batholith or stock has resulted from the differentiation of a syntectic magma.

In applying the hypothesis to the explanation of actual field occurrences other general considerations seem necessary. Stoping and abyssal assimilation on the batholithic scale are begun by the primary basaltic magma. This magma carries the heat required for the double action.† The source of the magma is to be found in the general basaltic substratum beneath the earth's solid crust.

These subsidiary elements of the problem here to be discussed have been described in the first intrusion paper and, more fully, in the later communication on 'Abyssal Igneous Injection.'‡ No one of these additional conceptions is essential to the idea of stoping *per se.* All of them may prove incorrect without invalidating the stoping hypothesis in its main feature. Combining them and the idea of stoping, the writer has constructed a general working hypothesis for the origin of the igneous rocks. It seems, therefore, expedient in the present chapter to discuss the problem in its larger aspect.

Believing that assimilation by magmatic action of some kind is responsible for practically all the chambers occupied by those intrusives with which he is more or less intimately acquainted, the writer has sought for field evidence as to

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* American Journal of Science, Vol. 26, 1908, p. 19.

† Again it may be noted that the question whether the substratum is actually or only potentially fluid is not vital in this connection. The observed rigidity of the planet may be due, not to its being a true solid, but to the direct influence of gravity, which binds the earth-shells so effectively that bodily tides are almost wholly prevented. In any case rigidity and solidity are not synonymous terms.

‡ Amer. Jour. Science, Vol. 22, 1906, p. 195.

whether any other sort of assimilation is possible than that by caustic or solvent action of a magma on its roof and walls. Such information is found in the same internal contact-belt where the general failure to prove solutional absorption of the country-rock has been so often reported. Within that belt it is the rule to find often very numerous blocks of the invaded rocks. These have usually the following characteristics: varying size; angular or subangular outlines against the eruptive rock, which is essentially unmodified even close to the contact with each block; sharp contacts with the eruptive, in which the blocks are completely immersed; a normally high crystallinity and increased density as a result of contact metamorphism. Very often they show that they have moved but short distances from the niches they once occupied in wall or roof. The molar contact is similarly sharp. It may preserve, with exceeding definiteness, the sharp corners left when the blocks were rifted off. Passing inwards, it is an equally normal thing to find the foreign inclusions to become rapidly rarer, until, in the heart of the eruptive area, one may go hundreds of yards or even several miles without discovering any such inclusions. If there are hundreds of them in a given part of the contact belt at the present surface (evidently a chance section exposed by erosion), the natural inference that there are thousands or millions of others enclosed in the eruptive below the level of the visible contact, is clearly permissible. Another legion of them has been destroyed along with their matrix in that part of the igneous body removed by denudation. It is manifest, further, that the rifting of the blocks has *so far* enlarged the chamber occupied by the eruptive. That is, the walls are, on the average, farther apart because of the rifting. The question arises as to whether the chamber may owe a large part of its present size to a long continuation of the selfsame process, with a simultaneous removal from the visible chamber of the blocks formerly rifted off. The affirmative answer to this question is the kernel of the hypothesis to be proposed.

Strangely enough, the explanation of the presence of foreign blocks within igneous bodies along the molar contacts and the equally conspicuous rarity of such fragments toward the centres of the bodies, has only quite recently been undertaken. How blocks still close to their former homes in the country rock could be suspended in the magma until crystallization of the latter was complete, and whether the normal effect of their complete immersion would be to permit of their floating upwards or sinking downwards in the magma, are questions of prime importance to the ensuing hypothesis. The attempt has been made to answer them by correlating experimental and other data acquired for petrological science within recent years. We may, for the present, assume the generally accepted liquidity of normal plutonic magmas.

Magmatic Shattering by Differential Thermal Expansion.—A clear statement of magmatic shattering has been given by Crosby in his monograph on the Blue Hills Complex.*

It is manifestly impossible to determine the exact rise of temperature which will occur in a formation at the contact with an invading magma. Both ele-

* Occasional Papers, Boston Soc. Nat. Hist., Vol. 4, 1900, p. 315.

ments, the pre-eruption temperature of the country-rock and the temperature of the magma itself, are partly indeterminate. If the former be regulated by the normal law of the vertical distribution of the isogeotherms, that temperature will be about 200° C. at a depth of four miles below the earth's surface—a rather liberally estimated average depth for the upper limit of a granitic magma chamber. If we assume that the temperature of an intruding magma is approximately that at which the rock resulting from its crystallization becomes thinly molten under plutonic pressures (an assumption apparently justifiable from the known properties of lavas and notwithstanding the presence of mineralizing agents), there should occur by conduction *at* the molar contact, a rise of temperature in the invaded formation, of something like 1000° C. That would mean a cubic expansion in the solid rock of between 2·5 per cent and 3·0 per cent, corresponding to a linear expansion of about 0·9 per cent. The force required to prevent that degree of expansion is equal to the amount of pressure required to compress the rock by the same amount. The coefficient of compressibility for ordinary crystalline and well-cemented sedimentary rock is not far from that of glass, viz.: about 0·0000025 per atmosphere of pressure. The pressure of more than 10,000 atmospheres, or about 75 tons to the square inch, would be required to prevent the expansion of rock raised 1000° C. in temperature.* However great the expansion transverse to the plane of the molar contact may be, a large proportion of the force of expansion must pass into the form of compressive strain, developing lines of force in the plane of the contact. The integrity of the rock must be destroyed, for its crushing strength would hardly average as much as 20 tons to the square inch. The action would be complicated and intensified by the variable values of heat-conduction in the invaded formation which is always more or less heterogeneous.

It has been objected that rocks are good conductors of heat and that, therefore, strong temperature differences with resulting rending strains are not to be expected in the shell of country-rock immediately surrounding a batholithic magma. The following table of coefficients of thermal conductivity seems, however, to show, on the contrary, that rock-matter is far from being ranked as a good conductor. The table has been made by compiling the values noted in the Landolt-Börnstein's Physikalisch-chemische Tabellen (1905 edition) and in Winkelmann's Handbuch der Physik. The values for the rocks are of the order expected in view of the familiar proofs of the extremely slow cooling of lava flows.†

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* Through a mistake in placing a decimal point the pressure was greatly overstated in the second paper on the 'Mechanics of Igneous Intrusion.'

† The steepness of the possible temperature gradient in the wall rock is shown by the fact that, a few days after lava ceases flowing, one can walk on its crust, although the lava just below is at red heat (700°–950°C.) or is yet hotter. For many hours or for several days the gradient at the surface may equal or surpass 500° C. per foot.

In the manufacture of calcium-carbide a mixture of limestone and coke is submitted to the action of a powerful electric arc. At the end of a furnace run (about fourteen hours in the plant at Ottawa, Canada) the flow of heat is nearly steady and the temperature gradient in the furnace is about 3000°C. per foot.

	k.
Silver, about	1·0000
Copper, about	·9480
Lead	·0836
Quartz	·0158
Marble	·00817
Granite	·00757 – ·00975
Gneiss	·000578 – ·00817
Sandstone	·00304 – ·00814
Basalt	·00673
Syenite	·00442
Glass	·00108 – ·00227
Water, about	·00130
Paper	·00031
Flannel	·00023
Silk	·00022
Cork	·00013
Feathers	·0000574

Weber has found that k for gneiss at 0° C. is 0·000578 and at 100° C. 0·000416, showing a very great lowering with increase of temperature.* In fact, through the interval 0° – 100° C., k seems to vary about inversely as the absolute temperature.† It is not impossible that the conductivity of rock at 1,100° C. approaches that of water, famous as a poor conductor. Thorough experimentation on this subject is urgently needed.

In the present connection the thermal diffusivity (κ) of rock, rather than its conductivity, is of first importance. If $s=$ specific heat and $d=$ density, we have

$$\kappa=\frac{k}{s.d}$$

For rock at room temperature (20° C.) Kelvin assumed 400 as the value of κ when the unit of length is a foot, the unit of time a year, and the unit of temperature one degree Fahrenheit. This value is close to that which represents the average of the determinations made for different rocks at room temperatures, during the years since Kelvin wrote his famous essay.‡

If κ be assumed as 400 at all temperatures up to 1300° C., it is possible to calculate the temperature gradient in the wall-rock of a molten batholith at the end of specified periods of time. For practical purposes the surface of contact may be regarded as infinite; let it further be considered as plane. Under these conditions the following Fourier equation furnishes the datum for calculating the temperature at a point x feet from the contact at the end of t years, if the magma is kept stirred by currents.§ In the equation b = the temperature of the

* Forbes and Hall have proved analogous relations for iron and for magnesium oxide; cf. J. D. Forbes, Trans. Roy. Soc. Edinburgh, Vol. 24, 1867, p. 105, and E. H. Hall and others, Proc. Amer. Acad. Arts and Sciences, Vol. 42, 1907, p. 597.

† Cf. P. G. Tait, Recent Advances in Physical Science, 2nd ed., London, 1876, p. 270.

‡ Trans. Roy. Soc. Edinburgh, 1862.

§ Cf. W. E. Byerly's Elementary Treatise on Fourier's Series, Boston, 1893, p. 86.

magma; c = the temperature of the wall-rock assumed as initially uniform; and u = the required temperature. We have:

$$u = b + (c - b) \frac{2}{\sqrt{\pi}} \int_0^{\frac{x}{2\sqrt{\kappa t}}} e^{-\beta^2} d\beta.$$

For values of $\frac{x}{2\sqrt{\kappa t}}$ which are less than 2·6 the value of the integral can be readily found from the table of the probability integral which appears in standard text-books on the Method of Least Squares. For the higher values of $\frac{x}{2\sqrt{\kappa t}}$ the value of the integral can, in many cases, be computed by developing it into a series. Kelvin's value for κ is peculiarly favourable for such computation and the corresponding units have been used by the writer in the calculations.

Let b = 2200° F. (about 1200° C.); c = 400° F. (about 200° C.); t = 1, 4, 16, and 100 years; and let x have the different values shown in the left-hand column of the following table (XLVII). The corresponding temperatures are shown in the other columns.

TABLE XLVII.—Showing values of u when κ = 400 and

x	t = 1 year.	t = 4 years.	t = 16 years.	t = 100 years.
0′	2200° F.	2200° F.	2200° F.	2200° F.
10′	1703	1947	2074	
20′	1263	1703	1947	
40′	683	1263	1703	
80′	408·5	683	1263	
100′	ca.400	537	1078	1703
160′	400	408·5	683	
200′	400	ca.400	537	1263
320′	400	400	408·5	
400′	400	400	ca.400	683

The table shows that, at the end of the first year, the temperature of the rock is but slightly affected by the magmatic heat at a point 80 feet from the contact, and that the temperature gradient for the 80-foot shell then averages nearly 23° F. per foot. At the end of four years the temperature is but slightly affected at a point 160 feet from the contact and the temperature-gradient is about 11° F. per foot.

But κ cannot be nearly so great as 400 in the case before us. We have seen that k decreases rapidly with rise of temperature in rock. The experiments of Weber, Bartoli, Roberts-Austen and Rücker, and Barus show that the specific heat of rock averages about ·180 at 20° C. and increases regularly with rise of temperature, so that at 1100° C. the specific heat averages about ·280.* It

* For references see J. H. L. Vogt, Christiania Videnskabs-Selskabets Skrifter, I. math.-naturv. Klasse, No. 1, 1904, p. 40.

follows that thermal diffusivity in rock decreases with rising temperature even faster than the conductivity decreases. For rock heated to 1000° or 1200° C. κ may not be more than 100 in the Kelvin system of units.

It seems safe to assume, first, that the diffusivity of the gradually heated wall-rock may vary from 275 or less to 100 or 150; secondly, that the average diffusivity of an 80-foot shell heated during the first year by adjacent molten magma, will be no greater than 200. If κ be regarded as averaging 200 for all periods greater than one year, the four columns showing values of u in the table will serve if t is, respectively, 2, 8, 32, and 200 years.

As a result of somewhat rigorous calculation, then, it appears certain that the heating of wall rock by plutonic magma must progress with great slowness and that the resulting temperature gradient in the shell adjoining the molten magma must be steep for many years after the original establishment of the contact.*

Further Lees has proved that rocks have highly variable coefficients of conductivity, some species possessing coefficients twice as high as those of other species.† It is also well known that bedded or schistose rocks conduct heat along and across their structure-planes at quite different rates. Where, therefore, the wall rocks about a batholithic mass are heterogeneous, the heat conduction is variable and expansional stresses must ensue.

Part of the stress-energy set free might be added to that of injection and expended in the minute crumpling of relatively plastic bedded country-rock. Another portion is conceivably expended in irregular and perhaps very complete shattering of the rock, which by that action is relieved from the strains by sudden rending and fracturing rather than by any form of rock flow. Still a third portion of the energy might become potentialized as in Rupert's drops, Bologna glasses, or certain slickensided rock surfaces,‡ and only finally expressed as a shatter-force after sudden faulting or other shock in the country-rock had precipitated the destruction, repeating on a large scale the destruction of a Rupert's drop.

Experiments and certain observations made in rock-quarries throw light on one of the more important and simpler methods by which disruption of the country-rock may take place. A short statement of the facts derived from each kind of study will be found in the writer's second paper on the 'Mechanics of Igneous Intrusion' (Amer. Jour. of Science Vol. 16, 1903, p. 114.)

Every city conflagration leaves manifold evidences of the shattering effects of the one-sided heating up of a rock mass—in columns, sills, and cornices of granite and sandstone. Telling illustrations have recently been published by

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* By using the same Fourier equation it is not difficult to show that the loss of thermal energy which a magma suffers by conduction into the country-rock is relatively small, even after the lapse of two or three hundred thousand years. The long duration of the magmatic period in a slightly superheated plutonic mass of large size becomes easily understood.

† H. Lees, Phil. Trans., Vol. 183 A, 1892, p. 481.

‡ A. A. Julien, Jour. Franklin Inst., Vol. 147, 1899, p. 382.

Humphrey.* He subjected panels composed of different dressed stones to rapidly and steadily increasing furnace-heat. After periods of but ten to forty minutes many of the stones spalled to depths of one to two inches, and all the blocks were badly cracked. Quenching with cold water or with draughts of cold air naturally increased both the spalling and cracking. The experiments show that quenching by water or cold air is not the necessary condition for the yet more remarkable spalling of stone in city fires.

It may be noted that the shattering of crystals and rock-fragments, when immersed in silicate melts, has often been observed.† The strains are, in such cases, necessarily of a lower order than those developed on the wall of a batholith where, therefore, shattering is even more certainly brought about. (See Plate 33).

Finally, the disruptive power of volatile matter contained in the wall-rock heated by batholithic magma, should be considered. This power may be very great.

In view of all the facts there seems to be a sheer necessity for believing in contact-shattering through differential heating and expansion in the thin shell of a country-rock which encloses a large body of molten magma. The evidence for the shattering is often exceedingly full and clear in the field. The broad or narrow belts of xenoliths so often found just inside the main contacts of batholiths are very hard to explain if those batholiths are due to laccolithic injection. The blocks are characteristically angular; they are generally not arranged with their longer axes parallel, as if they had been pulled off from the walls by the friction of the moving magma. On the laccolithic theory one would expect many of the xenoliths to form elongated smears in the granite rock. This is indeed occasionally seen but most exceptionally; as a rule the xenoliths have just that irregularity of form and arrangement which they should have if they had been shattered off by the hot magma just before its final consolidation. Throughout its long, earlier history the magma must, in every case, have had a much more effective shattering power.

Relative Densities of Magma and Xenolith.—In his first intrusion-paper, the writer published the results of his attempt to calculate the possible specific gravities of the chief types of molten magmas under plutonic conditions. The calculations were based on Barus's well-known fusion experiments on diabase. The specimen investigated had a specific gravity of 3·0178; when fused to a glass and cooled to 20° C., a specific gravity of 2·717. He further states that the glass‡ showed an expansion of 3·9 per cent in 'melting' and, as glass, expanded 0·000025 in volume for a temperature rise of 1° C. through the interval 0° – 1000° C. and 0·000047 in volume for 1° C. through the interval 1100° – 1500°. The 'melting' expansion (solidification-contraction) and the varying rate of expansion (or contraction) above and below 1000° C. seem to show that

* R. L. Humphrey, 'The Fire-resistive Properties of various Building Materials,' Bull. 370, U.S. Geol. Survey, 1909. See especially page 69 and plate 31.

† Cf. C. Doelter and E. Hussak, Neues Jahrb. für Min. etc., 1884, p. 18; A. Becker, Zeitschr. d. d. geol. Ges., Vol. 33, 1881, p. 62.

‡ 'Throughout this paper the molten rock solidifies into an obsidian.' C. Barus in Bull. 103, U.S. Geol. Survey, 1893, p. 26.

some crystallization of the melt took place during the experiment. Such crystallization was inevitable under the conditions of the experiment, in which the cooling lasted several hours. Barus's curves do not, therefore, show directly the volume changes suffered by pure diabase glass in passing from the molten isotropic state to the rigid isotropic state at room temperature. Excluding the 'solidification' contraction, the glass loses but 3·5 per cent of its volume in passing from the molten state at 1400° C. to room temperature; the loss of volume through the same temperature interval was calculated in the first paper as about 8 per cent. Barus found that the net decrease in specific gravity in passing from rock at 20° C. to glass at 20° C. was 10 per cent. For his diabase specimen, therefore, the decrease of specific gravity in passing from 20° C. to molten condition at 1200° C. is possibly only about 13 per cent, instead of about 16 per cent, as noted in the first paper.

Quite recently J. A. Douglas has made a number of very careful measurements of the densities of typical igneous rocks and of their respective glasses, all specific gravities being taken at room temperatures. Douglas's method is reliable and his results accordant. For gabbro he found the decrease of specific gravity, in passing from rock to glass, to be 5·07 per cent. Delesse had found the decrease to be 11·46 per cent, as the average of measurements of two specimens from different localities. Barus's determination, 10 per cent, is intermediate between the two.

It seems probable, therefore, that a decrease of 6 per cent in specific gravity (rock to glass at 20° C.) is close to the minimum for the average gabbroid rock, and it is possible that Barus's 10 per cent decrease is too high for average gabbro. For present purposes it is safer to use the minimum value of 6 per cent.

Among the most reliable of the older determinations are those due to Delesse and Cossa. These are noted as follows (Table XLVIII.).

For purposes of comparison the analogous results of the Carnegie Geophysical Laboratory experiments with minerals are given in tabular form (Table XLIX.) :—

TABLE XLVIII.

Specific gravities of rocks and glasses.

Authority.	Rock type.	Spec. grav. of rock.	Spec. grav. of glass.	Net decrease in density.
Delesse	*Granite*	2·730	2·450	10·26%
		2·623	2·360	10·03
		2·684	2·423	9·72
		2·680	2·427	9·44
		2·751	2·496	9·27
		2·700	2·447	9·37
		2·660	2·425	8·84
		2·643	2·478	6·24
Cossa	*Syenite*	2·710	2·430	10·33
Cossa	*Quartz diorite*	2·667	2·403	9·90
Delesse	*Diorite*	2·921	2·679	8·29
		2·799	2·608	6·82
		2·853	2·684	6·09
Delesse	*Gabbros*	3·100	2·664	14·06
		2·898	2·641	8·87
Delesse	*Gneiss*	2·821	2·625	6·95

TABLE XLIX.

Specific gravities of crystals and glasses.

—	Spec. grav. of crystal.	Spec. grav. of glass.	Decrease in density.
Artificial anorthite	2·765	2·700	2·4%
" albite	2·605	2·382	8·5
Purified natural quartz	2·654	2·213	16·6
Artificial orthorhombic amphibole	2·857		4·0
" " pyroxene	3·175	2·743	13·6
" monoclinic pyroxene	3·192		14·1
" diopside	3·275	2·830	13·6
Average of all seven	.....	.....	10·6

Summarizing all the results we have:—

TABLE L.

Decrease in density (rock to glass at 20° C.).

Diabase of Barus..	10·00%
Gabbro of Douglas..	5·07
Average gabbro of Delesse..	11·57
Average diorite of Delesse..	7·07
Average diorite of Douglas..	5·65
Quartz diorite of Cossa..	9·90
Syenite of Cossa..	10·33
Syenite of Douglas..	6·02
Tonalite of Douglas..	6·87
Average granite of Douglas..	8·78
Average granite of Delesse..	9·16
Gneiss of Delesse..	6·95
Average of all above..	8·85
Average of seven minerals (Carnegie Geophysical Laboratory) ..	10·6

We may conclude that the acid rocks certainly expand more than the basic ones in passing to the glassy state at room temperature. It is probable, though not certain, that the expansion of the more acid glasses with heating is not much more rapid that that of the basic glasses. In any case, we shall, in the following argument, make no mistake in principle if we assume that all the leading types of crystalline rocks expand at least as much as gabbro (or diabase) when molten at the high temperature of 1300° C.

Reade in a large number of determinations found that rock expands, on the average, at sensibly the same rate as that found by Barus for diabase, namely, about 0·000025 volume per degree Centigrade.* Using this figure, allowing for the various rates of decrease in density for the different rocks in passing into the glassy condition, and assuming that each glass expands, with heating, at the same rate as Barus's diabase, we have the data of Table LI.:—

TABLE LI.

Specific gravities of rocks and melts.

——	Specific gravity of crystalline rock at			Specific gravity of same rock when molten at			
	20°C.	1000°C.	1300°C.	1000°C.	1100°C.	1200°C.	1300°C.
Gabbro and diorite ..	2·80	2·73	2·71	2·57	2·56	2·54	2·53
	2·90	2·83	2·80	2·66	2·65	2·64	2·63
	3·00	2·92	2·90	2·75	2·74	2·73	2·72
	3·10	3·02	3·00	2·84	2·83	2·81	2·80
	3·20	3·12	3·10	2·94	2·92	2·91	2·91
Quartz-diorite and tonalite..... ...	2·70	2·63	2·61	2·46	2·45	2·44	2·43
	2·80	2·73	2·71	2·54	2·53	2·51	2·51
Syenite	2·60	2·54	2·52	2·33	2·32	2·31	2·31
	2·70	2·63	2·61	2·42	2·41	2·40	2·40
	2·80	2·73	2·71	2·52	2·51	2·50	2·50
Granite and gneiss...	2·60	2·54	2·52	2·31	2·30	2·29	2·29
	2·70	2·63	2·61	2·40	2·39	2·39	2·38
	2·80	2·73	2·71	2·49	2·48	2·47	2·47

* T. M. Reade, Origin of Mountain Ranges, 1886, p. 110.

Reade's coefficients enable us to calculate the approximate changes in specific gravity undergone by blocks of stratified and schistose rocks (common country-rocks about batholiths), as these rocks (arbitrarily regarded as still solid) assume the temperature of very hot magma (at 1300° C.) in which they are immersed (Table LII.):—

TABLE LII.

—	Range of sp. gr. at 20°C.	Range of sp. gr. at 1300°C. (solid).
Gneiss	2·60–2·80	2·52–2·71
Mica schists	2·75–3·10	2·67–3·00
Sandstone	2·20–2·75	2·13–2 67
Argillites	2·40–2·80	2·32–2·71
Limestone	2·65–2·80	2·57–2·71

Influence of Plutonic Pressures on Rock Density.—Before drawing any conclusions concerning the possibility of the flotation of foreign blocks of solid rock in a plutonic magma, it is clear that a preliminary stage of our inquiry must be passed. What influence has pressure at great depths on the *relative* densities of solid blocks and of the liquid magma in which they are immersed? One can hardly doubt that water and mineralizers in depth would increase such differences as those calculated for one atmosphere of pressure and 1400° C.; so that Gilbert's conclusion as to the difficulty of determining the densities of hydrothermally molten magmas need not affect the present argument except in a favourable way.* Since the temperatures of a block and its enclosing magma are practically identical, the final step in deciding on their relative densities in depth is taken, if it can be shown what is the relative compression suffered by the solid and liquid.

Again we must have recourse to the valuable experiments of Barus as those, of any known to the writer, most nearly related to the problem at issue. He concludes, as a net result of his investigations, that 'the relation of the melting-point to pressure in case of the normal type of fusion is nearly constant irrespective of the substance operated on. . . And in the measure in which this is nearly true on passing from the carbon compounds to the thoroughly different silicon compounds, is it more probably true for the same substance changed only as to temperature and pressure. In other words, the relation of melting-point to pressure is presumably linear.'† Accepting his inferences as sound, the fact remains that his experiments on thymol, naphthalene, and other carbon compounds can throw light on the behaviour of silicate magmas in other respects than that cited in the foregoing quotation. This important deduction is cor-

* G. K. Gilbert, Rep. on the Geol. of the Henry Mts., 1877, p. 76.

† Phil. Mag., Vol. 35, 1893, p. 306, and U.S. Geol. Survey, Bull. 103, 1893, p. 55; cf. Amer. Jour. Science, Vol. 38, 1889, p. 407, and Vol. 46, 1893, p. 141.

roborated by the proved similarity of silicates and carbon compounds, in (*a*) the linear relation of expansion to increment of temperature in the solid form of each substance, in (*b*) the linear relation of expansion to increment of temperature in the liquid form of each substance, and in (*c*) the sudden leap in volumetric increment in the act of melting at any temperature.

Barus further indicates that solid naphthalene is comparable in compressibility with the liquid form of the same substance.* His fusion curves show that, for the same increase of pressure, liquid naphthalene gains in specific gravity about twice as fast as solid naphthalene. The compressibility of a fused silicate rock is perhaps, then, twice that of the same rock when solid. But his diabase fusion curve demonstrates that the thermal expansibility of the liquid rock is about 1·9 times as great as that of the solid rock. Thus a block of cold, solid gabbro immersed in a deep-seated molten magma of the same chemical composition, would be less condensed by the pressure than the molten rock, but the effect on relative densities would be partly compensated by any superheating of the magma. Moreover, the compressibility of glass and of crystalline silicates is known to be very low. The compression suffered by glass, for example, is about ·0000026 of its volume for 1 atm. The weight of even 10,000 metres of rock with an average density of 2·75 would cause a density increase of much less than one per cent in glass. It is therefore probable that the difference of density between magma and immersed block would not be affected through pressure, at the great depth of 10 kilometres, by as much as 1 per cent of the density of either one.

Sinking of the Shattered Blocks.—It appears from Table LI. and LII. that nearly all xenoliths must sink in any molten granite or syenite; most xenoliths must sink in molten quartz-diorite, tonalite or acid gabbro. Many xenoliths might float on basic gabbro but the heavier schists and gneisses must sink in even very dense gabbro magmas at 1300° C.

Giving, then, the highest permissible values to the specific gravities of magmas, it is still true that blocks, such as are shattered from the wall or roof of a batholith, must sink when immersed in most magmas at atmospheric pressure.

It has been objected to the stoping hypothesis that the viscosity of granitic magmas is too great to allow of the sinking of blocks even much denser than those magmas. This objection has, however, never been sustained by definite experimental or field proofs. The xenoliths visible along batholithic contacts have assuredly not sunk far from their former positions in wall or roof and the reason for this must be sought in the high viscosity of the magma. High viscosity is an essential attribute of a nearly frozen magma. The phenomena of fractional crystallization and of magmatic differentiation unquestionably show that each plutonic magma must pass through a long period of mobility. The most viscous of granitic magmas, the rhyolitic, issues at the earth's surface with such fluidity that the rhyolite often covers many square miles with a single thin sheet. The absolute viscosity of the Yellowstone Park rhyolites must have

* Amer. Jour. Science, Vol. 42, 1891, p. 140.

been of a low order when many of these persistent flows were erupted. Nothing can seem more probable than that the relatively small fall in temperature, represented in the passage of a thinly molten magma to a toughly viscous condition, has actually taken place in plutonic bodies. Doelter has shown experimentally that that decline in temperature under surface conditions may be from 1240° C. to 1150° C. for granite, from 1070° to 1010° C. for phonolite, and from 1060° to 992° C. for basalt. The presence of water and other mineralizers in granitic magmas must add to their mobility, as held by many writers including Brögger, whose general argument for liquidity seems irrefutable.*

Even granting that the kinetic viscosity of a plutonic magma is thousands of times that of water, it could not support xenoliths more dense than itself. In a few days or weeks stones will sink through, and corks will rise through, a mass of pitch, the viscosity of which is more than a million of millions of times that of water.† Ladenburg has lately shown that small steel spheres will, in a few minutes, sink through twenty centimetres of Venetian turpentine, a substance 100,000 times as viscous as water.‡ Ladenburg's experiments have verified the generally accepted equation expressing the rate of sinking of a sphere in a strongly viscous fluid:

$$x = \frac{2}{9} \frac{gr^2 (d - d')}{v}$$

where x = the velocity of the sphere when the motion is steady; g = the acceleration of gravity; d = the density of the sphere; d' = the density of the fluid; r = the radius of the sphere; and v = the viscosity of the fluid.§. The equation shows that the velocity of sinking varies directly as the square of the radius of the sphere. This fact may be correlated with the observation so often to be made on granite contacts, that large xenoliths are rare. This apparently means that at the end of the shatter-period, the viscosity is truly so high as to allow of the smaller blocks being trapped at high levels in the freezing magma, while the large blocks, with greater velocity, shall have sunk into the depths.

Doelter estimates that the pressure of from 7,500 to 11,000 metres of rocks increases magmatic viscosity no more than 20 to 30 per cent.** If the increment be anywhere near this value we may be certain that the viscosity of superheated, plutonic magma is relatively low. G. F. Becker has calculated that the viscosity of a Hawaiian basaltic flow, not one of the most fluid, was, at eruption, about fifty times that of water. The more fluid rhyolite flows may have viscosity a thousand times greater than that of water. The corresponding viscosities of the same magmas when ten kilometres underground may, then, be possibly no more than a few thousand times that of water at the earth's surface. One must

* W. C. Brögger, Die Eruptivgesteine des Kristianagebietes, Vol. 3, 1898, p. 336.

† Jamin et Bouty, Cours de Physique, tome I, 2e fascicule, Paris, 1888, p. 135; cf. Daniell's Text-book of the Principles of Physics, 2d. ed., London, 1885, p. 211.

‡ Annalen der Physik, Vol. 22, 1907, p. 287.

§ Poynting and Thomson, Text-book of Physics, Properties of Matter. London, 1902, p. 222.

** C. Doelter, Physikalisch-chemische Mineralogie, Leipzig, 1905, p. 110.

conclude that a xenolith, even very slightly denser than such a plutonic magma, will sink into it. Since such magmas necessarily cool with extreme slowness, there is evidently good ground for believing that an enormous amount of solid rock could be engulfed before practical rigidity is established. The average xenolith must sink in a less dense magma with the viscosity of pitch—yet how much more rapidly in magma possessing the low viscosity which is postulated in any of the ruling theories of plutonic-rock genesis!

Rise of Magma through Stoping.—We may legitimately imagine that a shell of country-rock, say 100 feet thick, is thus stoped out of the roof of a batholithic chamber. The rock at the new molar contact must undergo similar one-sided heating and the stoping process is continued. By the summation of these relatively small effects the upper level of the magma would be raised, so long as the original supply of heat held out, unless the roof were finally punctured and engulfed. If the heat supply did not suffice to produce such a catastrophe, the form of the batholithic chamber would be that of a downwardly enlarging compartment within the invaded formation, though a pipe-like chamber could also be produced.

Stoping will vary in rapidity with the size of the blocks rifted. The average block near visible contacts is most probably smaller than the average block rifted during the much longer period of high fluidity in the magma.

But the development of the magmatic chamber is, after all, not so important for petrogenic theory as is the fate of the engulfed blocks. Nearly all of these must certainly be dissolved as long as the great mass of magma remains fluid. Such abyssal assimilation means the wholesale formation of new, secondary magma. This topic will be treated in a following section.

Testimony of Laccoliths.—In view of the extreme improbability that one can often, if ever, expect to find the pressure-solid, or otherwise determined floor of a deep-seated magma basin, it is of interest to question the few known laccoliths with visible floors for information as to the efficiency of stoping. Of course, the conditions for rifting and for the submergence of blocks from the roof, are much less favourable in the rapidly intruded magma of a typical laccolith than they would be in a deeper-seated magma in direct communication with the 'ewige Teufe.' Some notable degree of viscosity seems necessarily assumed as characteristic of laccolith magmas. The *proved* laccoliths are all small and are surrounded on every side, except at the narrow conduit, by cold rocks, so that chilling must be much more rapid than under plutonic conditions. Nevertheless, the attempt has been made to find, in the published descriptions of type laccoliths, any statement for or against the probability of a limited amount of rifting and stoping. In such small igneous bodies, it would be unlikely that total digestion would destroy blocks fallen from the roof. They might, therefore, be looked for on the floors. So far, the writer has discovered no evidence on the point in any of the monographs. The reasons are not far to seek. Very few floors of laccoliths are actually exposed. It is probable, too, that in many instances an observer would have difficulty in distinguishing blocks torn out of the floor from those sunk thither from the roof. Gilbert,* Jaggar,† and others describe fragments at levels above the floor, but do not directly raise the question as to how they were held suspended within the magma. In the laccoliths of the Henry mountains, the unusually low densities of the invaded sandstones and shales are such as to warrant the belief that fragments of these rocks really floated in the magma.

Jaggar has described large blocks of Cambrian strata as immersed in the laccolithic porphyries of the Black Hills and explains them as due to 'excessive doming.' Yet it is conceivable that they may owe their present positions to high magmatic viscosity, the magma freezing as they were in the act of slowly floating upwards from the floor or sinking from the roof of the laccolith.

So far, then, laccoliths have given chiefly negative evidence in the test of the stoping hypothesis for plutonic magmas, and, perhaps in the nature of the case, they can never be of great value in determining the truth of the hypothesis.‡

Problem of the Cover.—The stoping hypothesis presents an obvious principal difficulty; it refers to the apparent danger of the foundering of the roofs covering the larger batholiths. Under plutonic conditions (at depths of from one to five or six miles) the average molten granite would have a specific gravity no higher than 2·40. The average rock of its roof has a specific gravity of about 2·70. If, then, through orogenic movement, a large mass of the roof-rock became once wholly immersed in the granite, it would not only founder itself but through subsequent buckling the whole roof might collapse and founder in sections. Doubtless such a catastrophe has seldom happened in the case of any Paleozoic or later batholithic intrusion. This difficulty has been emphasized by Barrell, who justly gave it a prominent place in his monograph.§

The present writer cannot claim to have solved this problem, but he does not find it to form a fatal objection to the hypothesis. In the first place, it seems clear that all the other hypotheses of granitic intrusion are facing the same dilemma. All of them expressly or tacitly postulate some degree of fluidity in each granitic mass as it either replaces or displaces its country-rocks. We have seen that, though the viscosity of such a magma may be several hundred times that of water, the roof-sections, once immersed, must sink in the magma. All petrologists who believe in magmatic or other differentiation as operative in batholiths must face the common difficulty.

Secondly, the writer has shown reasons for believing that the earth's crust at present rests on a continuous *couche* of basaltic (gabbroid) magma, either quite fluid or ready to become fluid when injected into the crust. If the average specific gravity of the crust is 2·75 (a probable value), it would as a whole be quite able to float on the basaltic *couche,* which, under the great pressure, would probably have a specific gravity over 2·80. Imperfect as the numerical data

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* G. K. Gilbert, Geology of the Henry Mountains, 1877, p. 66.

† T. A. Jaggar, U.S. Geol. Survey, 21st Annual Report, Part 3, 1901, p. 211.

‡ Do the "muscovado" blocks on the floor of the Duluth gabbro "laccolith" of Minnesota in part represent sunken fragments of its roof?

§ J. Barrell, Prof. Paper, No. 57, U.S. Geol. Survey, 1907, p. 172.

are, we seem justified in concluding that the earth's crust is now, as a whole, in stable flotation.*

It may have been entirely different in pre-Keewatin (earliest Archean time, when the superficial, acid *couche* of the primitive earth began to solidify. Then foundering may have taken place, as Kelvin imagined, and the early formed crusts could have sunk half a score of miles or more until they met the denser *couche* below. Possibly some of the complexity of the pre-Cambrian formation may be referable to this unstable condition of the early crust. Already in Keewatin times the acid shell was solidified and was then penetrated by basaltic injections which reached the surface, forming the heavy masses of greenstones belonging to that period. Since then the crust has remained essentially coherent, and through it the primary basalt has, at many times and places, been erupted. It is, however, quite possible that the lack of system among the axes of the Laurentian batholiths and the abundance of those batholiths are both explained by the thinness and weakness of the crust in post-Keewatin and pre-Cambrian time.

For Paleozoic and later batholiths there is a well-defined law that they have penetrated the crust only on the sites of folded geosynclinals, and that the larger batholithic axes are usually arranged parallel to the respective geosynclinal and mountain-range axes.

In other words, the intrusion history of the globe may be conceived as divisible into three epochs: the first being that in which the outer primary shell was becoming stable through successive solidifications and founderings, the second being the post-Keewatin (Laurentian) epoch of very general interaction between the fluid basaltic substratum and acid crust, without extensive founderings but with development of many large, irregularly occurring batholiths; the third, a period of the localization of batholiths in certain mountain-built belts, where alone there seems, in this third period, to have occurred the injection of molten magma in masses of batholithic size—rarely, if ever, accompanied by wholesale foundering.†

Again, granting the hypothesis that a visible post-Archean batholith is the acidified, upper portion of a basaltic body originally injected to a level less than about six or eight miles from the earth's surface (perhaps the level of no strain), it is not difficult to see that extensive foundering may be impossible. Only after some differentiation or acidification of the primary magma would any part of it become less dense than the average roof-rock. Xenoliths of the heavier gneisses and schists would, however, sink. When dissolved in the primary magma their material—added to that dissolved along the main contact—would lower the density and inaugurate the stage of general stoping. Only

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* For a further discussion of this point see Amer. Jour. Science, Vol. 22, 1906, p. 201.

† Is it certain that the rhyolite plateau of the Yellowstone Park is not the site of partial foundering? The vastness of the formation suggests, in any case, that the youngest of the American batholiths lies but little below the surface in the Park. The geyser heat is probably derived from this still cooling batholith. Since this report was sent to Ottawa for publication, the writer has issued a fuller statement of this suggestion (Proc. Amer. Acad. Arts and Sciences, Vol. 47, 1911, p. 60).

when the resulting syntectic magma has been formed in large amount is there any danger of roof-foundering. But it is evident that, in the process of dissolving the engulfed blocks, the magma is losing heat. In the normal post-Cambrian batholith the magma, because of exhaustion of the heat supply, seems to have been arrested in its upward course at average distances of a few thousand feet from the earth's surface. The syntectic magma, less dense than the roof-rock, is thus necessarily of limited depth. That depth represents the thickness of the *couche* which endangers the stability of the roof. If, now, we imagine the buckling of the roof with the complete immersion and sinking of certain parts of it, the foundering must be limited by the width of the injected body (seldom over thirty miles) and by the thickness of the acid *couche* (perhaps eight miles or less). Extensive floods of rhyolite and allied rocks may have issued at the surface in consequence of partial foundering (faulting), but great crustal catastrophes involving large areas would not be expected.

Finally, it should be noted that post-Archean granitic intrusions have regularly followed periods of prolonged orogenic crushing, during which accumulated tangential stresses are effectually relieved. As the magmas work their way up into the folded terranes there is relatively little chance for the buckling of the roof. Until it is buckled and immersed in the magma it cannot sink. Now the heat of the magma, though it shatters the roof-rock at the immediate contact of solid and fluid, must tend to expand the roof, tighten it, prevent normal faulting and so strengthen the roof. The cover of the batholith is thereby kept in an exceptionally rigid condition. Its strength is, initially, that of a domed shell spanning diameters not very many times the thickness of the shell. The strength is increased, as with the groined roofs and arches of Gothic architecture, by the presence of roof-pendants; and by thermal expansion, the whole is strongly knit together. Immersion and foundering of roof-sections may, therefore, have been seldom possible in the case of post-Archean batholith or stock.

In spite of the highly theoretical nature of some of the foregoing argument, it appears to the writer to carry weight enough to warrant our regarding the difficulty in question as not destructive of the stoping hypothesis. The problem needs further study in connection with this and all other conceptions of granitic intrusion.

Supply of the Necessary Heat; Magmatic Superheat and its Causes.—Whether the observed average temperature gradient within the earth's crust is to be explained as due to original heat (inherited from an early epoch in the development of the earth either from a gaseous or planetesimal nebula), or whether the gradient is due to the evolution of heat with the break-up of radium and other radio-active substances, are general questions not immediately affecting the stoping hypothesis. We need go no further back in the thermal problem than to secure an estimate of the minimum temperature of the primary magma when abyssally injected and thus prepared for stoping and assimilation. This estimate is evidently not easy to make. A rough idea of the probable temperature may be obtained by deductively considering the temperature gradient or, secondly, by assuming that the initial temperature of the abyssally injected basalt is not far from that of the hottest basaltic lava known in volcanoes.

The first method is only applicable on certain assumptions as to the thermal and material constitution of the basaltic substratum. It is first of all assumed that the substratum, though a true basalt for many miles of depth, is faintly stratified according to density differences. The chemical contrast between successive shells of the substratum may be extremely slight and yet sufficient to prevent convection currents, even though the bottom shell of the substratum is several hundreds of degrees hotter than the uppermost shell. A rise in temperature of four hundred degrees involves an expansion of only about one per cent in volume. An underlying *couche* of basalt at 1600° C. would, therefore, if its specific gravity at 1200° C. were 2·93, not convectively displace an overlying *couche* of magma at 1200° C. and with a specific gravity of 2·90. Such faint density stratification, if assumed, goes far to explain the general stability of the earth's crust and so far is in accord with the facts of post-Archean geology. This conception also involves the possibility that the observed temperature gradient continues without important change, deep into the substratum. It is here also assumed that the gradient, 3° C. for 100 metres of descent, applies to the crust and to the upper part of the substratum at least. It must be noted, however, that the gradient may very considerably steepen in the depths, because of the fact that the thermal conductivity and diffusivity of rock both decrease in large ratio with increase of temperature. The amount of steepening of the gradient is unknown, but our ignorance on this point is unessential to the principle of the following argument, in which the normal gradient is assumed throughout.

Thirdly, it is assumed that, under normal conditions, the substratum shell immediately below the solid crust is not superheated but is at the melting point of basalt at that depth. The accepted temperature gradient gives, at the depth of 38 kilometres, a temperature of 1140° C. Vogt has calculated that the pressure at this level raises the melting point about 50° C. Since basalt at atmospheric pressure is all molten at about 1140° C., we may conclude that the bottom of the crust, in accordance with the assumptions, averages about 40 kilometres below the present surface. If the earth is cooling down, the crust was evidently somewhat thinner during Tertiary and pre-Tertiary batholithic intrusion.

If, now, a broad geosynclinal prism of sediments, 10,000 metres thick in the middle, is laid down on the site of a future mountain range, the isogeotherms must rise. The uppermost layer of the substratum, where most deeply buried, will thus tend to assume a temperature of nearly 300° C. above normal. If the sedimentary prism be folded and overthrust as in the usual large-scale orogenic disturbance, the substratum below the mountain range may be still more effectively blanketed, with a further rise of the isogeotherms. Quickened erosion may, however, largely offset this thickening by the mountain-building process, and it would be unsafe to postulate a total rise of temperature of more than 300° C. in the substratum of the area. Part of this superheat is lost by conduction into the crust, the lower basic part of which may be thus melted. An unknown but possibly considerable fraction of the total superheat may remain in the original substratum, and this amount of superheat would characterize the basalt when rapidly injected into the crust.

If, as generally believed, the earth's acid shell is specially radioactive, its evolving heat must tend to be retained beneath a geosynclinal blanket and local superheat in the substratum developed. Perhaps this is the principal cause for the enormous excess of thermal energy in batholithic magmas.

Another source of superheat is found in the conversion into heat of the mechanical energy necessary for injecting a viscous melt into an opening cavity.

These sources of superheat would alone furnish enough thermal energy to raise the injected basaltic magma from 1140° C. to some temperature short of 1500° C. or 1600° C.

The piling up of 10,000 metres of lava over a large area would have an analogous superheating effect on the substratum. This conclusion enables us to give some explanation of the fact that the lavas of Kilauea and Mauna Loa seem to be the hottest known in any volcanic vent. The vast Hawaiian lava plateau has, apparently, been built up by the comparatively rapid effusion of basaltic flows from Pacific depths averaging 6,000 metres to heights above sea of about 4,000 metres. The unique lava fountains of Mokuaweoweo, while showing obvious evidence of considerable superfusion, are described as glowing with 'white heat.'* If a correct description, this implies a temperature of 1300° C. or possibly 1400° C.† Such temperature must be a minimum for the substratum which feeds these vents, where there is continuous loss of heat in the convectively stirred lava.

Speculative argument and limited observations in nature agree, then, in fixing some such temperature as 1300° C. as a minimum for the basaltic mass injected into the crust-rock below a great mountain range. A batholithic body of this magma is thrust into rocks which have already been abnormally heated in the crush of mountain-building.

Capacity of Superheated, Plutonic Magma for Melting and Dissolving Xenoliths.—Basalt must have a thermal capacity much like that of diabase at the same temperature. Barus's experiments show that the average specific heat of diabase for the interval 1300–1140° C. is ·350.‡ The heat-energy contained in the substratum, if it be superheated 160° C. above its melting point (1140° C.), is in excess of that contained in the substratum just above its melting point by (160 × ·350=) 55 + gram-calories.

* J. D. Dana, Characteristics of Volcanoes; New York, 1891, p. 200.

† LeChatelier and Boudouard's High Temperature Measurements; New York, 1904, p. 246.

‡ C. Barus, Bull. 103, U.S. Geol. Survey, 1893, p. 53. For the interval 100-20°C., the mean specific heat is about ·185. There is, in fact, a steady increase in the mean value as the temperature of any silicate or silicate mixture rises. This fact goes far to explain the prolonged liquidity of assimilating magmas. Cf. J. H. L. Vogt in Christiania Videnskabs-Selskabets Skrifter, math. naturv. Klasse, 1904, No. 1, p. 40.

This surplus heat energy is available for the fusion and assimilation of country-rock. There are good reasons for believing that the average wall-rock of granite batholiths has the composition and crystallinity of a granitoid gneiss. For purposes of calculation this will be assumed to be the fact. The average temperature of the wall-rock before an abyssal intrusion may be conservatively estimated from the normal temperature gradient to be 200° C. In order to raise the gneiss to the temperature of 1200°, where it is just molten, about 410 calories (assuming latent heat at 90 calories—a value estimated by Vogt for the silicates) per gram must be supplied from an outside source. If all the superheat of the basalt were available for melting (not dissolving) gneiss. $\frac{55}{410}$ of mass-unit of gneiss would be melted by mass-unit of the superheated basalt; or about 7·5 mass-units of the basalt would melt a mass-unit of wall-rock.

Such simple melting would, however, not occur. There are plenty of field and laboratory proofs that molten basalt, even slightly superheated, will dissolve fragments of gneiss and allied rocks. The mutual solution of two contrasted silicate mixtures takes place at a certain temperature which is lower than the melting point of either one. The simple contact of two such materials suffices to cause their mutual solution at that lower temperature.* This fundamental law of physical chemistry has been experimentally demonstrated for silicates by Vogt and by Doelter and his pupils, although the last mentioned authors have, perhaps, not sufficiently regarded the fact that it takes considerable time for the mutual solution to take place.†

Petrasch has experimentally shown that, when two parts of limburgite and one part of granite are mixed and heated, they melt together at 950° C. and the solution remains fluid down to 850° C.‡ Predazzo granite softens at 1150°C. and the limburgite at 995° C.§ In this case, there is a lowering of 200°–300° below the melting point of granite and 45°–145° C. below that of limburgite.

It seems highly probable, thus, that gneiss-xenolith and basalt would form a solution or syntectic film which is molten at a temperature *at least* 100° C. below the fusion-point of basalt at the average depth of ten kilometres or less below the earth's surface. At those depths basalt melts at about 1150° C.; the syntectic would be molten at or below 1050° C. If the syntectic film were continuously removed during the sinking of the block or by the currents inevitably set up during stoping, nearly all of the superheat of the basalt might be used in dissolving the gneiss. The total melting-heat of gneiss, if molten at 1050° C.,

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* Cf. O. Lehmann, Wiedemann's Annalen der Physik, Vol. 24, 1885, p. 17.

† See J. H. L. Vogt, Christiania Videnskabs-Selskabets Skrifter math.-naturv. Klasse, 1904, No. 1, p. 191; and Tscherm. Min. u. Petrogr. Mitth., Vol. 24, 1906, p. 473.

‡ K. Petrasch, Neues Jahrb, für Min., etc., Beil. Bd. 17, 1903, p. 508. Petrasch mixed the powders of one part of granite (softens at about 1150°C.) with two parts of hornblende andesite (softens probably about 1050°C.) and found the mixture to become molten at 900°C., proving again an important lowering of the melting-point below that of either rock. Basic rock thus acts as a flux for granite (or gneiss) to an extent comparable with that proved by Petrasch and others for lithium chloride, calcium fluoride, ammonium chloride, and sodium tungstate.

§ C. Doelter, Tscherm. Min. u. Petrogr. Mitth., Vol. 20, 1901, p. 210.

would be about 400 calories. The heat energy required for the solution of one gram of the gneiss which has an original temperature of 200° C. is (400–40=) 360 calories. The heat energy given off by one gram of basalt in cooling from 1300° to 1050° C. is about (250 × ·340=) 85 calories. One gram or mass-unit of gneiss would, then, be dissolved by $\left(\frac{360}{85} =\right)$ 4·3 grams or mass-units of the primary basalt, provided all the thermal energy were used for solution.

These various calculations are obviously very crude. They take no account of conduction of heat away from the batholithic mass, nor any account of possible exothermic or endothermic chemical reactions between basalt and wall rock; nor any account of the influence of water, chlorides, etc., derived from any geosynclinal rocks which are assimilated.* These substances held in the magmatic solution tend to lower the solidification point of the syntectic. The result of the calculation would also be affected if we assume that the heavier xenoliths would sink to levels where the temperatures are above 1300° C. Finally, the result would be different if we postulate that the invaded formations, through the crushing incident to orogenic movement before the intrusion, had been heated above 200° C. Without here entering on the discussion of these further complications, we may conclude that probably from four to six volumes of the superheated primary basalt would furnish the heat-energy necessary for the solution of one volume of wall-rock.

If this rough estimate is even approximately correct, we have some idea of the actual assimilating power of plutonic magma which has been superheated a couple of hundred degrees. We also see a definite reason for the fact that post-Archean granites have seldom, if ever, stoped their way to the earth's surface. The crust has been too thick, the expenditure of heat energy in forming the syntectic magma too great, that the process could operate to its extreme and so endanger the stability of the roofs of most of these batholiths.

Objection Founded on Rarity of Evidences of Assimilation at Observed Wall-rocks.—One of the most commonly expressed objections to any theory of the replacement of invaded formations by batholithic magmas consists in emphasizing the obvious fact that the average xenolith and average wall-rock of batholiths do not show direct evidence of melting or of solution in the granitic magma. This objection has been answered by the writer in several publications† and also by Andrews in most vivid fashion.‡ The point has, however, been restated by several authorities without any adequate discussion of the subject. No one can deny that, when the magma is all but frozen, it is incapable of assimilating

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* According to the stoping hypothesis almost all of the heat conducted into the shells of country-rock successively stoped away during the magmatic period, is not lost, but is available for the abyssal assimilation of the engulfed blocks. In view of the slowness with which the mixtures of powdered silicates melt, it is probable that notable exothermic reactions do not take place. The possibility of endothermic reactions seems to be a more open question.

† Amer. Jour. Science, Vol. 15, 1903, p. 281; Bull. Geol. Soc. America, Vol. 17, 1906, p. 372.

‡ E. C. Andrews, Records, Geol. Surv. of N. S. Wales, Vol. 8, Pt. 1, 1905, p. 126.

xenolith or wall-rock on any large scale. The practical question is as to the magma's efficiency during the long antecedent period of its history. It is true that bed-ridden centenarians did not build the pyramid of Cheops; it does not follow that men did not build it.

If it be assumed that the quartz of granite has crystallized at or below 800° C.,* it follows that complete rigidity is not established in a granite batholith until it has cooled to at least 800° C. Down to about that temperature limit (of undercooling), therefore, magmatic stoping is still possible. The lowest limit of active assimilation cannot well be much below 1000° C., while the temperature required to melt the average xenolith is about 1200° C. As the viscosity of granitic magmas increases greatly below 1200° C., diffusion and convection must become rapidly inadequate to remove syntectic films at main contacts, so that the molecular lowering of the fusion-point will be confined, within the interval 1200°–800° C., chiefly to the sunken blocks. It follows, first, that in the very long period of time occupied in the cooling of a plutonic mass from 1200°C. to 800° C., there will be little or no melting or solution of wall rock; secondly, that many shells of roof-rock, perhaps aggregating thousands of feet in thickness, may be stoped away during that same period of time. In other words, because the shatter-period is longer than the period of active assimilation at the roof, it is an essential feature of the stoping hypothesis that neither visible xenolith nor main wall of a granite batholith should normally show a collar of assimilation. So far from being a difficulty, the fact that this is generally true is a distinct argument in favour of the stoping hypothesis.

Abyssal Assimilation.—In the first paper on the stoping hypothesis the writer stated grounds on which one must believe in the complete solution of engulfed xenoliths. One has only to imagine a block of gneiss, say ten metres in diameter, sinking through a column of superheated basalt twenty or thirty kilometres deep, to become convinced of the ultimate fate of that block. If the somewhat cooled lavas described by Lacroix,† von John,‡ Dannenberg,§ Sandberger** and others could dissolve rock-inclusions in the notable way described by those authors, we must credit a vast solutional efficiency to plutonic magma when it attacks similar blocks in great depth. The lava has a few hours or days in which to do its work; the abyssal magma has centuries if not a large part of a geological period!

It must be remembered that geosynclinal sediments are rocks unusually rich in water, chlorides, sulphur trioxide, etc.; all substances aiding solution in the primary magma and in the secondary (syntectic) magma itself. It is probably also owing to these fluids in large part that granitic magmas have crystallized at comparatively low temperatures.

The conception of stoping with abyssal assimilation has many more points

* Cf. A. L. Day and E. S. Shepherd, Jour. Amer. Chem. Soc., Vol. 28, 1906, p. 1099.
† Les Enclaves des Roches Volcaniques Macon, 1893.
‡ Jahrb, d. k. k. Reichsanstalt, Vienna, Vol. 52, 1902, p. 141.
§ Tscherm, Min. u. Petrogr. Mitth., Vol. 14, 1895, p. 17.
** Sitzungsber. K. Bair. Akad. Wiss., 1872, p. 172.

in its favour than can be cited for pure marginal assimilation. A few of the special grounds for preferring the newer to the older hypothesis may be noted.

First, marginal assimilation is largely effective only in the earliest part of the magma's history, when it is absolutely and relatively very hot. There is thus an early time-limit fixed for the gigantic work of dissolving the thousands of cubic kilometres actually replaced in the intrusion of a large batholith.

Secondly, the assimilation, on the older view, takes place primarily on main contacts and along a relatively limited amount of surface. For example, a cube of wall-rock one kilometre in diameter can offer only about 1,000,000 square metres of surface at a time to the dissolving magma. If that same cube were shattered into cubes 10 metres on the side and then engulfed, the magma would carry on the work of solution on 600,000,000 square metres of surface.

Thirdly, the average crust-rock being allied chemically to gneiss, is more soluble in basic magma than in acid. On the stoping hypothesis, solution of the xenolith generally occurs in the lower, basic part of the magmatic chamber; on the older view, it is granitic magma which must do most of the work of solution. For even if the originally injected magma is a basalt, the products of its assimilating activity, being more acid and less dense than itself, must remain at the batholithic roof and rapidly assume the chemical composition of mean mountain-rock. It follows that the primary magma must be enormously more superheated than is required on the stoping hypothesis or than seems easy of explanation, in view of the difficulty of understanding how plutonic magma, which is capable of intrusion, can become superheated more than two or three hundred degrees Centigrade.

Fourthly, the stoping hypothesis has the special advantage of providing a mechanism of thorough agitation within a batholith. Strong stirring of the mass is induced by the sinking of xenoliths and by the necessary rising of the magma locally acidified by their solution. This agitation can explain the marvelous homogeneity in each large batholith. It helps greatly to explain the manifest evidences of magmatic differentiation within batholiths—splittings and segregations that cannot be due to the slow process of molecular diffusion or to mere thermal convection. The whole process of stoping and the rising of syntectic magma tends to equalize the temperatures in the batholithic chamber and thereby we can understand the even grain and rapid, nearly simultaneous crystallization of a batholith throughout its visible depth.

Fifthly, the engulfment of blocks of geosynclinal sediments enriches all parts of the batholiths with water, chlorides, etc., which so greatly aid solution; while, on the older view, these agents are confined to the uppermost part of the chamber.

Sixthly, as already noted, the cleansing of syntectic films from contact of solid and liquid is much the more rapid and perfect according to the stoping hypothesis, thus providing and renewing conditions for molecular lowering of the fusion-point along contacts.

In short, the newer view has the advantage of not only better explaining the facts of the field but it is incomparably more economical of the heat postulated for the work of batholithic replacement than is the theory of pure marginal assimilation. Melting and marginal assimilation of country-rock takes place in the initial, superheated condition of a basaltic injection but must be regarded as always subordinate in replacement efficiency to stoping and abyssal assimilation.

Existence of Basic Stocks and Batholiths.—Finally, the fact that some large bodies of plutonic rocks are basic has been advanced as an objection against the idea of stoping.* This fact early impressed itself on the present writer and led to his reviewing the geological literature to determine, if possible, the number, distribution, and age of these bodies. It was found that most of those which appear to have batholithic development on a large scale are of pre-Cambrian age and are chiefly anorthosite intrusions. In the American Journal of Science, vol. 20, 1905, p. 216, the guarded suggestion was made that the anorthosites of Canada and the Adirondack mountains are so basic because of the absorption of crystalline limestones. On maturer consideration this suggestion seems inadequate and a more general explanation must be sought.

Adams describes the great anorthosite mass of Morin, Quebec, as genetically associated with an adjacent gabbro body of batholithic size.† The one is either a differentiate from the other or both are expressions of a common basic magma. The latter seems the more probable relation. In fact, both bodies appear to represent the crystallized products of a magma allied to, if not identical with, the primary basaltic magma which has been the source of the heat in post-Archean batholithic intrusions.

The conditions of intrusion for these 'upper Laurentian' masses seem to have differed from those typically represented in the post-Cambrian batholiths. The latter have been developed under heavy geosynclinal covers which have entailed considerable superheat in the basaltic substratum. It is not impossible that the 'upper Laurentian' basic magmas, already cooled nearly to the solidification-point, were injected into the then thinner crust, or warped up with it, during crustal disturbance. Lacking superheat these magmas lacked assimilating power and, consequently, did not become acidified.

In favour of the conception that these magmas were near the solidification-point at the time of their intrusion, is the fact that the anorthosites often show primary banding and are most extraordinarily granulated, as if by dynamic force which acted on the congealing mass near the close of the intrusion-period. Concerning the granulation Adams writes:—

> 'There are no lines of shearing with accompanying chemical changes, but a breaking up of the constituents throughout the whole mass, though in some places this has progressed much further than in others, unaccompanied by any alteration of augite or hypersthene to hornblende, or of plagioclase to saussurite; these minerals though prone to such alteration under

* W. Cross in Science, Vol. 25, 1907, p. 620.
† F. D. Adams, Canadian Record of Science, 1894-5.

pressure remaining quite unaltered, suffering merely a granulation with the arrangement of the granulated material in parallel strings. This process can be observed in all its stages, and there is reason to believe that it has been brought about by pressure acting on rocks when they were deeply buried and very hot. The anorthosite areas, of which there are about a dozen of great extent with many of smaller size, are distributed along the south and southeastern edge of the main Archean protaxis from Labrador to Lake Champlain, occupying in this way a position similar to that of volcanoes along the edge of our present continent.'*

Cushing and Kemp have published somewhat detailed accounts of the anorthosite forming a post-Grenville and pre-Cambrian body and its satellites in New York State.† The mass covers about 3,000 square kilometres in area. Cushing's petrographical descriptions show many points of agreement with Adam's description of the still larger Canadian bodies. The anorthosite generally crystallized with exceptionally coarse grain and a porphyritic structure. Intense granulation is here again the rule, and from Cushing's published data, it seems probable that the granulation followed hard after the act of intrusion. The characteristics and field relations of the anorthosite are such as to suggest that they have resulted from abyssal injections of magma which was not superheated. A limited amount of stoping is possible in such a magma but extensive assimilation of country-rock is not possible for that magma.

Kemp has suggested that the New York anorthosite has, through fractional crystallization and the settlement of the basic minerals of early generation, been derived from a normal gabbro.‡ This idea may possibly explain the existence of the more pyroxenic phase regularly occurring inside the body. The contact rock is either gabbro or anorthosite-gabbro. It may represent the original magma but little affected by the settlement of the crystals of iron-ore, pyroxene and olivine. In the more slowly cooled interior of the mass their settlement could take place on a large scale.§ In the Canadian bodies this differentiation by fractional crystallization may have occurred just before the huge masses were injected into the crust.

Finally, the masses of anorthosite may represent enormous laccoliths, like the Duluth gabbro as interpreted by Van Hise and Leith; therewith lacking most of the assimilative power of the bottomless batholiths. It is also not

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* F. D. Adams, Jour. of Geol., Vol. 1, p. 334, 1893.

† H. P. Cushing, 18th Report of the State Geologist, Albany, 1900, p. 101; New York State Museum Bulletin No. 95, 1905, p. 305. and Bull. 115, 1907, p. 471. J. F. Kemp. 19th Ann. Report, U.S. Geol. Surv. Pt 3, 1899, p. 409

‡ Op. cit., p. 417.

§ As noted in a later section (page 772), the same conception is adequate to explain many internal basic contact-phases occurring in acid stocks and batholiths. This explanation is evidently opposed in principle to the prevailing view that the basic contact-shells are due either to diffusion of basic molecules toward cooling surfaces, or to the combined influence of fractional crystallization and convection currents in the magma. Neither of these hypotheses seems acceptable in the case of the anorthosite-gabbro batholiths, and the writer has come to question their validity as final explanations for some other types of intrusive bodies.

impossible that these anorthosite bodies are the sites of crustal foundering which occurred before much assimilation had been accomplished.

The problem of the anorthosites is clearly as yet one for speculation rather than one capable of final solution. It seems proper to believe, however, that, since all or nearly all of the known anorthosite and gabbroid batholiths are of pre-Cambrian age, they owe their origin to special pre-Cambrian conditions. The stoping hypothesis as a whole expressly relates only to conditions which have characterized orogenic belts in post-Archean time.

The gabbros of Paleozoic or later age represent bodies either too small or of too low temperature to carry on extensive stoping before their magmas became rigid. Diorite stocks and batholiths, according to the hypothesis, represent undifferentiated or but partially differentiated syntectic magma—of composition intermediate between rhyolite or granite and basalt.

These various considerations incline the writer to the view that the existence of a few large basic intrusions, cutting acid rocks, is not necessarily a fact fatal to the stoping hypothesis. Each of the cases needs special study, for they may shed much light on the difficult plutonic problem.

Differentiation of the Syntectic Magma.—In order to trace further the history of the engulfed xenoliths several principal conditions must be recognized. If the invading magma is superheated, so as to have the temperature of 1300° C., a block of heavy gneiss (sp. gr. at 20° C., 2·85) will speedily be heated to and above its own melting-point. While some of it is dissolved, much of it is converted into a molten globule of essentially pure gneiss. From Table LI. we see that the specific gravity of the globule would be about 2·40, while that of the surrounding primary magma would average about 2·72. This difference of density means that the globule must rise through the primary magma with a speed even greater than that with which the solid rock (specific gravity about 2·75) formerly sank.* As it rises the globule would wholly or partly mix with the primary magma. If wholly mixed the primary magma rapidly becomes a syntectic magma, approaching a diorite in composition. The molecular, syntectic film which is formed by solution along the surfaces of the block must, theoretically, contain about equal parts of primary magma and xenolith material. If the former be basalt and the latter a granitoid gneiss, the film must have a dioritic composition. All three kinds of secondary magma—molten globules of gneiss, globule material dissolved in primary magma as the globule rises, and the material formed in the molecular, syntectic film—must be considerably less dense than the primary basalt and rise toward the top of the batholith chamber. A net result of abyssal assimilation is a compound, secondary magma either dioritic or more acid than diorite.

This reasoning is deductive but it can in some measure be checked by actual observations. Lacroix describes blocks of gneiss up to a cubic metre in size, which have been immersed in molten basalt. By the heat of the lava the blocks

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* The same reasoning applies to xenoliths of normal gneiss immersed in acidified gabbro or diorite magma.

have been 'entirely transformed' into porous glass.* Von John has described other examples of the same transformation. In chapter X. the present writer has correlated a considerable number of instances where the gravitative stratification has certainly been produced in thick intrusive sheets.

A number of observers have come to the conclusion that the very act of the assimilation of acid material by basalt predisposes the magma to magmatic splitting. The fullest statement of this view is given by Loewinson-Lessing, in his remarkable 'Studien über die Eruptivgesteine.'† There appears to be, as it were, a steady 'antagonism' between the ferromagnesian and acid-alkaline elements in magmas. This primordial tendency toward immiscibility may well explain the dominant acidity and alkalinity of the pre-Cambrian terranes in every continent. From the earliest times the granito-rhyolite magma has tended to separate from the basaltic wherever the viscosity has been sufficiently low for such splitting. For similar reasons it appears that the syntectic magma of post-Archean batholiths only reaches a stable condition when it assumes the ancient relation. In the average case the fluidity has been high enough for the splitting. In some cases, however, it was so low that the undifferentiated syntectic has crystallized as diorite and allied rocks.

When the syntectic has differentiated, the process must be primarily controlled by density, so that the acid, generally granitic, product rises to the top of the chamber. There it may become locally further differentiated through fractional crystallization or other relatively subordinate process.

Without discussing the causes of differentiation in more detail it suffices to point out, in summary, that magmatic stoping involves the placing of gravity at the head of the list of forces which produce the actual diversity among igneous rocks. In this the stoping hypothesis is believed to match the facts observed in experimental, industrial and geological studies of silicate melts.

Origin of Granite; the Petrogenic Cycle.—The stoping hypothesis involves a more or less definite corollary relating to the genesis of granite as the staple visible material of post-Archean batholiths. Erosion has nowhere penetrated more than a few thousand feet in any of these batholiths. Considering the scale of operations, it follows that practically all post-Archean batholithic rock is of secondary origin. The field relations show that the granite often replaces much geosynclinal sediment. Thick as many geosynclinal prisms are, however, it seems clear that another large, probably the larger, part of the replaced rock is the pre-Cambrian crystalline terrane (averaging granitoid gneiss in chemical composition) which underlies geosynclinal areas, as it apparently underlies all the continental areas. The similarity of granites throughout the world may, indeed, be partly explained by the uniformity of the earth's primordial, acid shell and by the relative uniformity in average chemical composition of the greater geosynclinal prisms.

A speculation as to the acid shell is noted on pages 702 to 705. It views the shell as possibly an anchi-eutectic derivative of an intermediate (andesitic)

* Les Enclaves des Roches Volcaniques, p. 563-5; Macon, 1892.
† Compte Rendu, Congrès géol. internat, VIIe session, St. Petersburg, 1899, p. 375.

magma which enveloped the metallic core of the earth before a true crust was formed. If modern augite andesite is a differentiate from basalt we can similarly regard the possibility that, under certain conditions, bodies of liparitic or granitic magma are the extreme differentiates from the basalt of the substratum. The association of andesite with pitchstone and quartz felsite of the composite dikes of Arran is one of many occurrences significant in this connection.* The field relations of the average batholith are such, however, as to compel belief in assimilation on a large scale. We seemed forced to believe that the differentiation of syntectics, rather than the differentiation of primary basalt, has produced the greater masses of post-Archean granite. The chemical resemblance of the average acid pole of this splitting to the primary acid earth-shell† is understood if, in both cases, the anchi-eutectic, granite, separates by liquation and rises. Where sediments only are assimilated, the secondary granite may be of abnormal composition; this is the case with the granite of the Moyie sills.

The longer an abyssally injected and assimilating body holds its fluidity, the more perfect should be the gravitative differentiation. During this active stage lateral fissures or laccolithic spaces may be filled with offshoots of the slowly changing magma. In general these satellitic injections should succeed each other in the order of increasing acidity. In a fully represented petrogenic cycle at a batholithic area, then, the oldest intrusion should be a rock of gabbroid (basaltic) composition and the youngest an acid granite (chemically a rhyolite or quartz porphyry). Between these two an indefinite number of intermediate rock-types varying according to their degree and kind of differentiation from the syntectic—itself continuously varying in composition—might be represented in dikes or other satellitic forms. This further deduction from our hypothesis seems to be fairly matched by the observed order of igneous intrusions about the world's batholiths.

Again, successive batholithic intrusions in the same area should show the same law of increasing acidity with decreasing age. If, for example, a crystallized granodiorite batholith be itself attacked by a later abyssal intrusive and in large part stoped away and remelted, the secondary magma collecting at the roof of the later batholith should be more acid than the granodiorite. This would be expected because the mere act of remelting entails further gravitative differentiation. Each time that a silicate mass passes through the optimum temperature for magmatic splitting—probably an interval of one or two hundred degrees above its melting point‡—the separation of its acid-alkaline and ferromagnesian elements by gravity is further perfected. Morozewicz has given a telling experimental demonstration of the process. He melted two pounds of granite and left the superheated melt in a hot part of an active glass-furnace for five days. It was then cooled to a glass. At the end of the time he found

* J. W. Judd, Quart. Jour. Geol. Soc., Vol. 49, 1893, p. 536.
† See Cols. 1, 2, and 3, in Table XLIV.
‡ F. Loewinson-Lessing, Studien über die Eruptivgesteine, p. 380.

that the lower part of the melt carried 59·20 per cent of silica, the upper part 73·65 per cent; the original granite showed 68·9 per cent.*

It is, however, to be expected, on the stoping hypothesis, that the primary basaltic magma may close an entire petrogenic cycle, since the latest phase of a batholith, after crystallizing, may be fissured and injected with a small volume of the substratum. The common occurrence of diabase or porphyrite dikes in granite may be thus explained.

Eruptive Sequence.—The various eruptive sequences observed in the Boundary section all seem to accord with this general deduction from the stoping hypothesis. The longest series is that in the Okanagan igneous complex, where the order of eruption for the batholiths is clearly that of decreasing specific gravity of the rocks. (See page 471). Seven other sequences are here tabulated; in each case the eruptives are named in order, beginning with the youngest.

Skagit Range.

(a) Sumas granite.
Sumas diorite.

(b) Chilliwack granodiorite.
Sleese diorite.

(c) Acid monzonite.
Skagit volcanics, chiefly basic andesite.

Columbia Range.

(a) Rock Creek granodiorite.
Rock Creek gabbro and diorite.

(b) Smelter granite.
Cascade granodiorite.

(c) Syenite-porphyry chonolith and dikes, cutting more basic Coryell syenite.
Rossland monzonite and latites.
Fife and Baker gabbros.

(d) Sheppard granite.
Trail granodiorite.
Basic intrusives and older Rossland (basic) lavas.

The discussion of the meaning of any eruptive sequence must be based on a more or less definite idea as to what constitutes a petrogenic cycle. Certain it is that much confusion has resulted from the common reference of *all* the eruptives in a given region to one cycle. This view is one product of the pure-differentiation theory, which excludes any essential amount of assimilation in the formation of rock magmas. The hypothesis of assimilation by a primary basaltic magma involves the possibility of several or many petrogenic cycles in a province. Each cycle opens with an abyssal injection of pure basalt. According

* J. Morozewicz. Tschermak's Min. und Petrog. Mitt., Vol. 18, 1898, p. 232. Cf. C. Doelter, Petrogenesis, Braunschweig, 1906, p. 79.

to the size and superheat of this body it will develop syntectic magma and, in the end, freeze up. The next cycle opens with a new injection of basaltic magma.

To discern the first and last products of a cycle among the actual formations of a province is evidently a difficult matter. In general, if two eruptive masses are separated in time by several geological periods it is unsafe to regard them as of one cycle. In compiling the foregoing illustrative list, therefore, only those bodies, which by their evident consanguinity and by their relatively close relation in age, have been considered.

Furthermore, the list does not include the host of complementary dikes often associated with batholiths and stocks. These are best regarded as pure-differentiation products and afford no direct test of the general theory. Even the sequence of the larger bodies noted in the list generally proves only a successive differentiation in depth. The point here made is that the law of the differentiation is the same as that necessitated by the stoping hypothesis (gravitative differentiation of syntectics, increasing with time). So far, these actual sequences all corroborate the hypothesis. In those cases, however, where a younger batholith or stock replaces an older batholith, the splitting of the syntectic formed by this assimilation may be expected normally to produce a rock in the younger body which is less dense (generally higher in silica and alkalies) than the older body. Such is the case with the Cathedral-Similkameen combination, the Smelter-Cascade combination, and the granite-diorite group of Sumas Mountain. The principle is further illustrated by many other provinces, as in the diorite-syenite-granite sequence at Ascutney Mountain, Vermont.* In fact, no eruptive sequence known to the writer, in any part of the world, is of a nature opposed to the view that assimilation by primary basalt, coupled with the principle of magmatic differentiation, is an essential condition for the origin of magmas and of igneous rocks.

Origin of Magmatic Water and Gases.—Finally, the stoping hypothesis implies that, since post-Archean batholiths have generally replaced large volumes of sediments, the volatile matter which is normally trapped within a geosynclinal prism should form an important part of the secondary magma.

An approximate idea of the amount of volatile matter in the average argillite,† sandstone and limestone of the world is readily obtained. For this purpose we may use Clarke's composite analyses of 843 limestones, of 624 sandstones, of 27 Mesozoic and Cenozoic shales and of 51 Paleozoic shales, together with 38 analyses of various argillites from different parts of the United States.‡ From these analyses the writer has determined, for the argillites, the average amount of water below 110° C. (H_2O-), water above 110° C (H_2O+), carbon dioxide, carbon (and carbonaceous matter), and sulphur (in SO_3). These averages represent, respectively, 116, 116, 106, 78, and 78 typical specimens of argillite from as many localities. The averages for sandstone and limestone

* Bull. 209, U.S. Geol. Survey, 1903.
† The term 'argillite' here includes both shales and slates.
‡ F. W. Clarke, Bull. No. 228, U.S. Geol. Surv., 1904, p. 20.

have been taken directly from Clarke's work and all three sets are noted in the following table:

An inspection of the table makes it clear that the total of the 'combined water,' carbon dioxide, carbon and carbonaceous matter, sulphur and chlorine in the stratified rocks exposed in any geosynclinal prism must represent at least six

TABLE LIII.—*Volatile matter in sediments.*

	843 limestones	624 sandstones	116 argillites
H_2O-	·26%	·29%	1·25%
H_2O+	·73*	1·41	3·71
CO_2	38·03	2·64	2·45
C (including carbonaceous matter)	?	?	·81
S	·11	·03	·25
Cl	·01	trace	trace
Total	39·14	4·37	8·47

* Includes organic matter.

per cent of the whole mass. It is highly probable that this minimum amount of volatile matter has similarly characterized such a series ever since the period in which the series was deposited.

No petrographer needs to be reminded that none of the commoner types of igneous rock contains anything like six per cent of original volatile matter. Nevertheless it is instructive to survey the facts actually visible in quantitative analyses of the igneous rocks. Water is the only volatile substance determined in igneous-rock analyses often enough to afford nearly reliable world-averages. From Osann's compilation the writer has deduced the aver ge of H_2O- and H_2O+ for each of the following groups: 48 granites, 47 diorites, 12 gabbros, 24 basalts, 5 augite andesites and 11 rhyolites (Table LIV).

TABLE LIV.—*Water in igneous rocks.*

	H_2O-	H_2O+
Granite	·17%	·64%
Diorite	·19	1·20
Gabbro	·26	1·35
Basalt	·73	1·03
Augite andesite	·40	1·48
Rhyolite	·30	1·23

Clarke's averages for the volatile substances occurring in igneous rocks which have been analyzed according to approved methods are:

H_2O-	·40%
H_2O+	1·46
CO_2	·52
S	·11
Cl	·07
F	·02

Much of the combined water, probably all of the hygroscopic water, and some of the carbon dioxide of these analyzed igneous rocks are due to alteration or to absorption at the earth's surface. Allowing for that fact, it seems probable that none of the more widely distributed igneous rocks carries much more than one per cent of its own weight in volatile matter directly derived from the earth's interior.

It follows that an enormous amount of water, carbon dioxide and carbon and sulphur compounds may be given off each time that geosynclinal sediments have been assimilated by molten and then crystallized magma. From each cubic mile of assimilated sediments about six per cent by weight of liquids and gases must be dissolved in the syntectic magma and, as crystallization proceeds, a large part of this fluid must be expelled.

In less important degree we may expect that the remelting or solution of an igneous rock by an intrusive magma should cause the evolution of some of the fluid matter which had been, as it were, frozen into the solid rock. Lincoln has aptly called such fluids 'repressed emanations.'* Gautier's and Brun's experiments show that many and probably all igneous rocks give off gases on being highly heated.† Reheating after cooling causes the renewed emanation of gases. Volatile matter trapped in crystallized secondary granite may thus be driven off, if that granite be dissolved in a younger molten magma with subsequent crystallization of the syntectic.

The stoping hypothesis in its broadest statement demands, therefore, that post-Archean, batholithic granites, syenites, and diorites should be accompanied by special evidences of fluid emanations.

These fluids were deposited and buried in the strata. They have been resurrected in their activity. They have 'risen again,' both literally and figuratively; they may be called '*resurgent*' emanations. The 'repressed' emanations of secondary igneous rocks may similarly be liberated by the distilling action of younger magma; as these fluids become revivified in their geological activities they may be regarded as forming a second kind of 'resurgent' emanations. All 'resurgent' emanations are of secondary origin and, therefore, stand in contrast to 'juvenile' emanations, namely, those which, for the first time, have issued from the earth's interior and become geologically active on or near the surface. Magmatic emanations are, apparently, divisible into two great classes, both of which should be recognized in complete discussions of ore-deposits.

That the stoping hypothesis stands this further test seems to the writer entirely clear. The prevalence of quartz veins and pegmatites in the walls and roofs of actual granitic, syenitic, and dioritic stocks and batholiths, and the intensity of the contact metamorphism produced by the intrusions of, and especially the emanations from, these rocks are facts as familiar as the comparative rarity of quartz veins and pegmatites about gabbroid masses and the comparative feebleness of the contact metamorphism produced by gabbros. The

* F. C. Lincoln, Economic Geology, Vol. 2, 1907, p. 268.

† A. Brun, Archives des Sciences Phys. et nat. Geneva, May and June, 1905 and November, 1906; A. Gautier, Annales des Mines (6), Vol. 9, p. 316, 1906, and Econ. Geol., Vol. 1, 1906, p. 688.

abundant water found in obsidian and rhyolite is, in this view, largely or wholly of secondary origin. Volcanic gases may similarly be largely 'resurgent' rather than 'juvenile.' In no case, however, would one class of emanations be represented to the exclusion of the other. For post-Archean granites the emanations are dominantly 'resurgent'; for gabbros the emanations are largely or dominantly 'juvenile.'

General Remarks on the Stoping Hypothesis.—The principal field-relation on which the foregoing discussion hangs is the 'replacement' of country-rock by magma in the intrusion of stock or batholith. Slow digestion and solution on main contacts has caused the replacement to a limited degree, but the facts of nature seem to enforce belief in the more rapid and more important mechanical replacement through magmatic stoping.

The suggestion that batholithic magmas work their way up by stoping is by no means new, and it is significant that, without any known exception, all the authors advancing it have done so quite independently and as the result of considerable field experience. Part of the idea was put forward by Kjerulf in letter though not in spirit as early as 1879.* In 1894, Goodchild wrote:—'Once the rocks [the deeper-seated rocks] are reduced to the molten condition they tend to eat their way upward and in any direction of least resistance—the place of the material flowing upwards being at first taken chiefly by the colder masses of rock, which sink within the magma as fast as they are quarried from the sides of the vent.'† In 1896, Lawson mentioned the idea of the sinking of blocks as a partial explanation of replacement. The statement was made in a review and has been quoted in full in the present writer's first paper on the mechanics of igneous intrusion (p. 283).

A detailed study of the phenomenon as exhibited in the Elkhorn district, Montana, was made by Barrell during the year 1900. His paper was withheld from publication. From the manuscript he later published the following summary:—

> 'The contact [of the Elkhorn granite] is in its larger proportion a broken and irregular surface slanting beneath a sedimentary cover, and it is probable that at no great depth the granite underlies the greater part of the district. If the granite merely broke through and involved the original rocks of the area it now occupies, their entire absence from it as inclusions is remarkable; if they had been carried away by fresh accessions from below they should be found as inclusions in certain localities preserved from erosion. On the supposition that they have sunk as fast as freed, the absence of inclusions may be readily explained. If, on the other hand, the batholith were an intrusive mass of limited thickness, its bottom should somewhere be exposed with the heaps of roof blocks resting upon it. As a matter of fact, no indications of a bottom have been observed anywhere within this batholithic area, and, although the evidence is negative in char-

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* T. Kjerulf, Udsigt over det sydlige Norges Geologi, Christiania, 1879.
† J. G. Goodchild, Geol. Magazine, 1894, p. 22.

acter, it must be taken as confirming to a certain degree the hypothesis that practically there is no bottom.

'According to these views, the few small inclusions close to the margin are those last detached and prevented from sinking by the increasing viscosity of the cooling liquid. A block once well away from its original position would not be held stationary, since the greater heat and liquidity at short distances from the borders would permit a freer fall.'*

Barrell was finally allowed to publish his masterly monograph on the Marysville stock, in which paper he shows, with unrivaled completeness, the pertinent actual field relations which can be seen in a small body of this kind.† He discusses the alternative hypotheses of batholithic intrusion and arrives at results which are practically identical with the views of the present writer. He did not consider the necessary consequence of stoping, namely, abyssal assimilation.

The present writer's statement of the hypothesis was published in the American Journal of Science for 1903 and in Bulletin 209 of the United States Geological Survey the same year. A supplementary paper was published in the American Journal of Science in 1908. Since 1903, Andrews in Australia, Barlow and Coleman in Ontario, Ball in Colorado (Georgetown Quadrangle), Calkins in Idaho, (Coeur d'Alene District), and others working in Canada and the United States have found the stoping hypothesis helpful in explaining field-relations.

But the stoping-syntectic hypothesis cannot account for the rise of magma through the whole of the twenty miles of earth-crust, which is the minimum vertical distance between the substratum and the visible batholithic roofs. Granting that the outer shell of the earth, one or two hundred miles in thickness, is in approximate thermal equilibrium, the heat supply of the substratum is incompetent for such a prodigious work. The great basaltic floods which have flowed out from fissures evidently did not reach the surface by assimilating the acid shell overhead. That, notwithstanding their patent superheat, they assimilated but minimal amounts of this shell shows that they issued rapidly, through *narrow* fissures in the acid shell. This old principle of abyssal injection has long been recognised, but has seldom been phrased in terms of a primary basaltic substratum. If, now, we imagine abyssal injections of the same nature as those underlying basaltic lava fields but much larger (wider), the phenomena of stoping and assimilation necessarily ensue. Some molar-contact assimilation must also take place, but for the reasons above detailed, should not rival abyssal assimilation in the preparation of secondary magma.

The combined processes of abyssal injection and assimilation must produce bottomless magma chambers. This deduction is abundantly supported by all the known facts about granitic rocks, and the separation of subjacent bodies in the classification of intrusive formations seems to be genetic and, therefore, demanded.

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* J. Barrell, Professional Paper No. 57, U.S. Geological Survey, 1907, p. 170.
† J. Barrell, Prof. Paper, No. 57, U.S. Geol. Survey, 1907.

CHAPTER XXVII.

MAGMATIC DIFFERENTIATION.

Preliminary Note.—We have now arrived at the conception that the post-Keewatin magmas have been of two kinds; the primary basaltic and the secondary syntectic. This idea rests on a much firmer basis than does the speculation that the primary acid and basaltic shells were the products of the differentiation of an intermediate (andesitic) magma early in the earth's history. The speculation is not important for the theory of the visible igneous rock bodies, which are almost entirely of post-Keewatin age. There remains the enquiry as to the extent to which differentiation has been responsible for the chemical diversity of eruptive rocks other than those solidified directly from primary basalt or from the syntectic magmas.

The subject of differentiation has prompted many papers and books from hundreds of geologists, who have established the reality of the process beyond peradventure. They have also proved its complexity. Fortunately there have appeared, during the preparation of the present chapter, two convenient résumés of the subject, one by Harker, the other by Iddings.*

By the time these pages are printed both of these works will be thoroughly familiar to every serious worker in the petrology and geology of eruptive masses. In each case the work is so complete on this side of petrogenesis that there is no need for a discussion of differentiation in the present report. It may be noted in passing that neither author gives an adequate treatment of the syntectic theory which, in some respects, has been best outlined by Loewinson-Lessing in his 'Studien über die Eruptivgesteine.'†

In view of the accessibility of these and other discussions of differentiation, the main generally accepted principles will here be stated without detail.

1. Relation to Crystallization.—The course of differentiation is, in general, parallel to the order of crystallization in the parent magma. This law has been discerned inductively and has become fundamental in petrology, since it agrees with the recently elaborated principles of physical chemistry. As a rule the ferromagnesian and cafemic (calcium-iron-magnesium) constituents separate out as crystals before the salic constituents, which remain for a time as mother-liquor. In fact, the formation of every crop of magnetite, titanite, augite, or olivine crystals means a new magma chemically different from the one preceding.

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* A. Harker, The Natural History of the Igneous Rocks, New York, 1909; J. P. Iddings, Igneous Rocks, New York, 1909.

† Compte Rendu Congrès Géol. Internat. VII[e] Session, St. Petersburg, 1899, p. 375.

2. Limited Miscibility.—Ostwald points out that the number of liquids miscible only within definite limits is much greater than is the number of those which mix in all proportions.* Since magmas are solutions it is *à priori* wise to consider their possible differentiation through the principle of limited miscibility at certain temperatures. Though Vogt has held that this principle does not, in general, apply to silicate mixtures, one of his latest publications contains the statement that, while separation of minerals follows the eutectic law, the 'mineral in excess' separates out while still in the liquid phase.† He further holds that magmatic differentiation is chiefly the result of just this kind of separation. Unless the writer misapprehends his meaning, Vogt has come to recognise limited miscibility as a general law for silicate solutions so soon as these approach the consolidation point of temperature. Ostwald and Richards believe that crystals develop from a transitory liquid phase in the case of substances which melt at temperatures not far from the temperature of crystallization.‡

From Durocher's time to the present many investigators have agreed in favour of limited miscibility of components in molten magmas. In view of the great difficulties surrounding experiments with molten silicates, including the granting of sufficient duration to an experiment, he is a bold physical chemist who denies the possibility of the separation of liquid components through the entrance of immiscibility at certain temperatures (and pressures). Without pursuing this theme in chemical dynamics it suffices to point out that the actual rocks in nature show unequivocally that separation by limited miscibility, a true magmatic splitting, has taken place, often on a great scale. This is true of silicate magmas splitting from silicate magmas as it is true of sulphidic or metallic melts separating from silicate magmas.

Most basic segregations and probably all orbicular granites, diorites, and gabbros are direct evidences of the emulsion stage, which precedes the separation of immiscible liquids with fall of temperature. The common banding of nephelite syenites, the banding of certain gabbros, the phenomena of some differentiated dikes (Entmischte Gänge), are other illustrations of this splitting in liquid magmas. The constitution of the Moyie sills or of the Sudbury sheet is inexplicable except on the assumption of immiscibility of granitic (micropegmatitic) and basaltic (gabbroid or noritic) magma under certain conditions. (See chapter X). Bäckström's point that there is a lack of intermediate rocks in the liparite-basalt field of Iceland has great significance in this connection.§ Finally, the evidence of silicate melts in glass factories is conclusive as to the main principle.

No one will, of course, deny that silicate melts are miscible in all proportions at high enough temperatures. The question is as to whether the average magma tends to assume the emulsion state within, say, one or two hundred

* W. Ostwald, Solutions, 1891, p. 39.

† J. H. L. Vogt, Videnskabs-Selskabets Skrifter, I, Math.-Naturv. Klasse, No. 10, Christiania, 1908, pp. 6, 16, and 102.

‡ T. W. Richards. Philosophical Magazine, 1901, p. 500.

§ H. Bäckström, Jour. Geol., Vol. 1, 1895, p. 773.

degrees of its 'solidification point.' Harker's objection that differentiated rocks are seldom sharply separated by distinct surfaces of contact is not a strong one. In the first place, the separation between such silicate differentiates *is* in many cases remarkably sharp, especially when we consider the scale of operations in magmatic chambers. Secondly, we could hardly expect the separation to be as perfect between these viscous and highly complex magmatic fractions as is, for example, the separation between phenol and water. In summary, it may be stated that a host of field and laboratory observations favour the application of the liquation (limited miscibility) principle to natural silicate magmas; and that not a single fact is known to the writer which conflicts with that assumption. The efforts of physical chemists should be spent, not on denying its validity, but in defining the conditions under which the liquation so often demonstrable in nature has taken place.

3. Gravitative Differentiation.—Gravity is one of the controlling forces in separating crystals from their mother-liquors. Illustrations of this truth are given in the writer's paper on the 'Origin of Augite Andesite and Related Ultra-basic Rocks.'* A striking example has since been reported from the New Jersey diabase, by Lewis.† The sinking of crystals is expected to have its maximum differentiating effect within volcanic vents, where the agitation of the magma tends to prevent undercooling and to promote crystallization while the magma retains relatively low viscosity. These conditions are chiefly due to the upward passage of gases in volcanic vents, which in this respect are contrasted with dikes, sheets, and laccoliths. The steady or intermittent working of two-phase convection within the lava at surface vents is, as we have seen (page 711), competent to keep the column long within the temperature interval of crystallization. The writer believes, therefore, that Darwin's theory of fractional crystallization under the control of gravity, is a permanent acquisition to the petrology of effusive rocks.

It is generally agreed, however, that differentiation is, as a rule, a splitting into liquid fractions. For example, it is impossible to believe that the drastic differentiation in the Moyie sills or in the Sudbury sheet (see chapter X.) can be due to the settling of solid crystals.

In volcanic vent or intrusive body gravity must tend to separate the liquated fractions. The lighter always rising to the top of the magma chamber, the geologist will rarely be permitted to see the rock representing the basic, heavier differentiate in subjacent bodies. He may find it in the form of dikes cutting the overlying, more rapidly solidified differentiate.

The relative importance of fractional crystallization and liquation can be estimated only after the physical chemistry of magmas becomes better understood. Meanwhile, we may use the expression 'gravitative differentiation,' as a name for the chief process in magmatic separation, without therewith implying whether fractional crystallization or liquation is the more active in a given case.

* Jour. Geology, Vol. 16, 1908, p. 411.

† J. V. Lewis, Ann. Rep. State Geologist of New Jersey for 1907 (1908), p. 129.

Origin of Basic Contact-shells.—The writer believes that the principle of gravitative differentiation is destined to supplant more and more the principle of diffusion in petrogenic theory. That, for example, basic contact-shells in intrusive bodies are due to the diffusion of ferro-magnesian and cafemic constituents toward the contact surface (Ludwig-Soret principle), is generally not the best explanation, is illustrated in the often quoted case of Square Butte, Montana.* Pirsson now explains the alkaline (sodalite) syenite of the core of this laccolith as derived from a basic magma by a combination of crystallization, convection currents, and settling-out. Calculation shows that the original magma had a composition like that of the leucite basalt which occurs as lava flows in the region. Shonkinite forming the lower, thicker part of the laccolith is the complementary product of the differentiation. The present writer is rather inclined to the view that, in this case, the two complementary masses separated in the liquid phase, rather than that the shonkinite represents sunken phenocrystic material. Ready calculation shows that, within a still liquid laccolithic mass, the possible differences of density induced by contact cooling are extremely minute. The true convection-currents must therefore be very feeble; and the period of their activity must be short.

The view that this differentiation has been due to a kind of liquation, accompanied by a gravitative separation of the heavier and lighter fractions, does not involve such an unfavourable condition. The process may be summarized as follows: A leucite-basalt magma was injected in a liquid state. On all sides of the laccolith it froze quickly, giving a basic contact-shell. The interior part, much longer fluid, was cooled until it reached the temperature of liquation (just above the point of solidification), and the splitting took place. This hypothesis implies that the basic rock at the roof had the composition of a leucite basalt. But the roof and this upper basic layer have both been completely eroded away so that it is not possible to test the truth of the inference.

The Shonkin Sag laccolith shows the same kind of differentiation.† In this case the roof and upper basic shell are still preserved. Pirsson describes the vertical section at the middle of the laccolith as follows:—

	Thickness in feet.
a. Leucite-basalt porphyry	5
b. Dense shonkinite	5
c. Shonkinite	5-6
d. Transition rock	3
e. Syenite	25-30
f. Transition rock	15
g. Shonkinite	60-75
h. Leucite-basalt porphyry	15
Total	140

The syenite forms only about one-nineteenth of the laccolith. The small difference chemically between shonkinite and leucite basalt would make it

* L. V. Pirsson, Bull. 237, U.S. Geol. Survey, 1905, pp. 53 and 189.
† L. V. Pirsson, ibid., p. 47 ff,

difficult to prove that the 'shonkinite' shells of *b* and *c* is not really a granular continuation of the porphyritic shell *a*. All three shells may represent the original magma, which in the center has differentiated, giving shells *d, e, f* and *g*. The analyses of *b* and *c* have not been published.

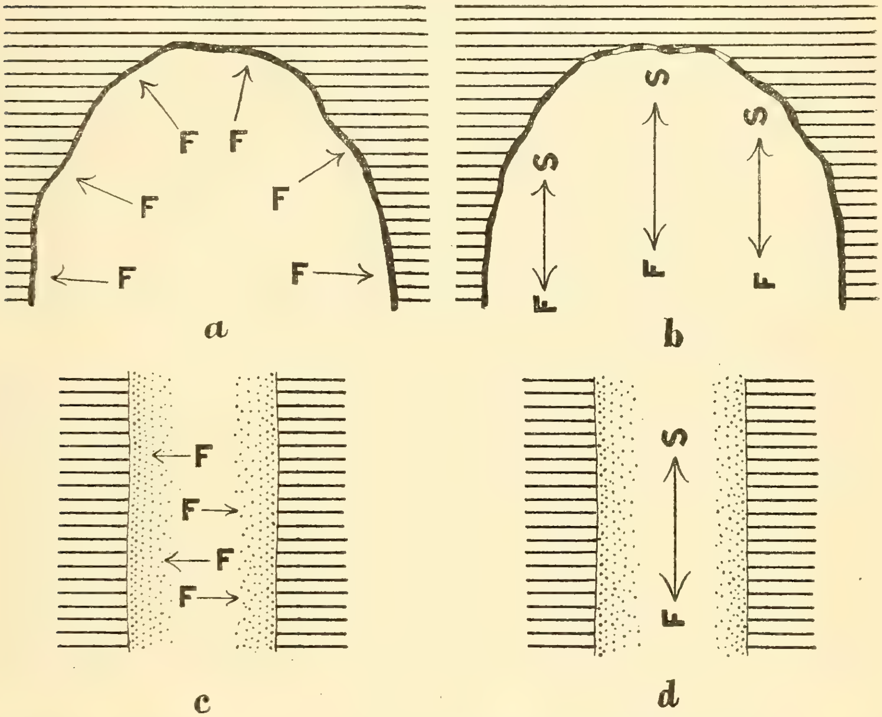

FIGURE 42.—Illustrating two methods by which basic contact-shells in a stock (*a* and *b*) or a dike (*c* and *d*) might be formed. Arrows show directions of movement of salic (S) and femic (F) constituents during differentiation.

Diagrams *a* and *c* represent the prevailing conception of contact-basification, that is through diffusion of more basic material to cooling surface.

Diagrams *b* and *d* illustrate the hypothesis that the basic contact-shell represents magma which was chilled at the molar contact and was not so thoroughly differentiated into salic and femic poles as the middle part of the mass.

In *a* and *b* the heavy black line represents the basic contact-shell; in *b* it is broken at the roof, to suggest the probable effect of resurgent gases in furthering differentiation.

Whatever be the exact method of the differentiation, the high probability of gravitative control is shown by Pirsson's ably assembled facts. Further, as his monograph shows, this conception gives the key to the origin of many other igneous bodies in the Highwood mountains.

Using the experiments of Gouy and Chaperon as a basis, Walker has offered a similar explanation of basic contact-shells in intrusive masses.* Substituting for the Gouy and Chaperon's principle the principle of liquation (or limited miscibility within a certain range of magmatic temperature), the present writer finds Walker's explanation applicable to the vast majority of basic contact-shells in the larger injected and subjacent bodies.

Each of these shells may, then, be regarded as that part of the magma in which marginal cooling checked gravitative differentiation, while the more slowly cooled magma occupying the great central part of the magma chamber underwent a more thorough separation of the salic and femic constituents. Examples have been noted in the Osoyoos batholith (page 441), the Similkameen batholith (page 457), and the Castle Peak stock (page 494). Contact 'basification' has often been observed in large vertical dikes, where the combined influence of contact chilling and gravitative differentiation may again be the explanation. The strong chemical contrast between wall phase and middle phase and the structure of many dikes suggest, however, that the differentiation has been facilitated by special concentration of gases in the interior part of each dike. In such cases the volatile matter doubtless increased the fluidity and hastened the magmatic splitting.

The accompanying diagrams (Figure 42) will make the conception clearer.

Chemical Contrast of Plutonic and Corresponding Effusive Type.—To gravitative differentiation we may ascribe the steady chemical differences between plutonic rocks and the corresponding effusives. The latter must come from the highest levels of magma columns. They are, accordingly, somewhat richer in silica and alkalies, and poorer in iron oxides, lime, and magnesia than their respective deep-seated equivalents. This important fact is illustrated in Table LV. The chemical contrast between the respective pairs of rocks can hardly be explained as the result of mere diffusion on the Soret principle or any other. Diffusion undoubtedly controls the growth of crystals but only rarely can it be credited with the segregation of special magmas on the scale of igneous-rock bodies.

* T. L. Walker, Amer. Jour. Science, Vol. 6, 1898, p. 410.

TABLE LV.

Showing the average chemical compositions of the more important plutonic and effusive rocks. The corresponding types are arranged in pairs.

—	Granites.	Liparites.	Syenites.	Trachytes.	Alkaline Syenites.	Keratophyres.	Laurvikites.	Rhomb-porphyries.	Monzonites.	Latites.
Number averaged.	236	64	50	48	23	7	3	7	12	10
SiO_2	70·47	73·72	60·90	61·46	62·46	63·06	57·85	58·24	55.62	58·18
TiO_2	·39	·30	·68	·38	·56	·46	.....	......	·60	1·01
Al_2O_3	14·90	14·10	16·47	17·97	18·07	17·81	21·26	19·79	16·64	16·84
Fe_2O_3	1·63	1·45	2·77	2·67	2·24	1·97	2·91	6·56	3·05	2·31
FeO	1·68	·83	3·32	2·66	2·31	3·43	2·41		4·40	4·11
MnO	·13	·12	·14	·06	·08	·01	......	......	·15	·10
MgO	·98	·40	2·52	1·13	·97	1·29	1·07	1·30	4·23	3·25
CaO	2·17†	1·34	4·35	3·13	2·57	1·11	4·13	3·15	7·24	5·79‡
Na_2O	3·31	3·59	4·03	4·49	5·58	5·36	5·93	6·44	3·50	3·62
K_2O	4·10	4·09	4·54	5·81	5·02	5·42	3·90	4·52	4·14	4·43
P_2O_5	·24	·06	·28	·24	·14	·08	·54	......	·43	·36

Each sum = 100·00. † Includes ·06% BaO and ·02% SrO. ‡ Includes ·16% BaO and ·07% SrO.

—	Nephelite Syenites.	Phonolites.	Granodiorites.	Dacites.	Diorites.	Andesites.	Gabbros.	Basalts.	Essexites.	Trachydolerites.
Number averaged.	43	25	12	30	70	87	41	198	11	4
SiO_2	55·38	58·65	65·82	67·67	57·56	60·35	48·95	49·87	48·86	55·62
TiO_2	·87	·42	·55	·33	·85	·78	·98	1·38	1·73	·43
Al_2O_3	20·16	21·03	15·99	16·81	16·90	17·54	18·15	15·96	16·83	20·31
Fe_2O_3	3·42	2·40	1·66	2·47	3·20	3·37	3·21	5·47	5·36	4·04
FeO	2·23	1·05	2·69	1·35	4·46	3·17	6·04	6·47	6·09	1·96
MnO	·35	·13	·05	·04	·13	·18	·13	·32	·15	......
MgO	·88	·31	2·19	1·23	4·23	2·78	7·62	6·27	4·52	2·35
CaO	2·54	1·53	4·71	3·31	6·83	5·87	11·15	9·09	9·14	5·68
Na_2O	8·38	9·02	3·86	4·18	3·44	3·63	2·59	3·16	4·49	5·94
K_2O	5·54	5·34	2·32	2·53	2·15	2·07	·90	1·55	2·15	3·18
P_2O_5	·25	·12	·16	·08	·25	·26	·28	·46	·68	·49

Each sum = 100.00.

Expulsion of Residual Magma.—Harker has suggested a third way in which gravity may affect differentiation.* He writes:—

> 'Any differentiation which depends on the sinking of crystals under gravity belongs necessarily to a somewhat early stage of crystallization, when the bulk of the magma was still in a liquid condition. At a later stage, when the crystals formed are so numerous or so large as to touch and support one another, the condition may be likened to that of a sponge full of water; and it is easy to picture a partial separation being effected by the straining off or squeezing out of the residual fluid magma from the portion already crystallized. That such a process does in fact take place is amply proved by the phenomena of pegmatites, which represent the final residual magma of plutonic intrusions.'

The squeezing out is regarded as specially noteworthy if the freezing magma is subject to pressure from movements of the earth's crust.

4. Effect of Solution of Foreign Rock.—The fourth of the primary laws affecting differentiation has been stated with unusual force by Loewinson-Lessing.† He holds that in many instances magmatic differentiation is induced by the absorption of foreign rock. This exotic material may bring about liquation in the original magma which, as a whole, may have suffered little chemical change by the assimilation. Here, as in many other points, Loewinson-Lessing's summary of petrogenic theory shows keenness, profundity, and breadth of view, which are seldom rivalled in other general works on igneous rocks.

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* A. Harker, Natural History of the Igneous Rocks, 1909, pp. 323-27.

† F. Loewinson-Lessing, Compte Rendu, Seventh Session, Congres géol. internat., 1899, p. 380, etc.

CHAPTER XXVIII.

GENERAL THEORY OF THE IGNEOUS ROCKS AND ITS APPLICATION.

Condensed Statement of a General Theory.

It is convenient to summarize the leading conclusions of the foregoing chapters, as to the origin of the rocks erupted during and since the Keewatin division of pre-Cambrian time.

Igneous bodies are intruded in two different ways: by displacement of the country-rock; and by its replacement.

Displacement takes place with two kinds of injection: abyssal and satellitic. Abyssal injection is the prelude of all igneous action of Keewatin and later date. Dikes, sheets, laccoliths, chonoliths, etc., are satellitic injections from abyssally injected bodies.

Replacement takes place in two ways: by marginal assimilation and by stoping with abyssal assimilation. In both cases the amount of replacement of country-rock is conditioned by the size of the body and is at a maximum for the greater abyssal injections which preserve direct thermal communication with the basaltic substratum. Marginal assimilation is almost entirely confined to the early, more or less superheated stage of the invading body. Stoping with abyssal assimilation, both in notable degree, must continue much longer, or until the magma at the molar contact is very highly viscous. For this and other reasons it seems that stoping is a much more effective agent in replacement than is marginal assimilation. If the magma be superheated the two kinds of replacement must co-operate. Batholiths and stocks generally represent the upper parts of abyssally injected bodies where their magmas have assimilated the invaded formations. The pre-Devonian (generally pre-Cambrian) anorthosites may possibly represent abyssal injections, which were initially too cool to assimilate any considerable amount of the intruded granites, gneisses, etc. Replacement in moderate degree has been carried on by thick sheets of magma, but, in general, bodies satellitic from the abyssal injections are too small to have assimilated large volumes of country-rock.

Vulcanism is initiated in two ways: by the mechanical opening of fissures, or by gaseous perforations of the roofs of intruded bodies. The largest lava fields have been formed above abyssal injections which reached from the level of the primary substratum to the earth's surface; in these cases the fissures permitting abyssal injection were continuous with fissures opening at the surface, and the lava is generally basaltic. Smaller fissure-eruptions may occur where the roofs of satellitic intrusions are cracked and the lava may be of many different chemical compositions. If the roof of a batholith is fissured some time after its abyssal injection has taken place, floods of liparitic (rhyolitic) lava result. The possibility is recognized that certain areas on the earth may have been the scenes of the foundering of batholithic roofs. Such foundering must have been more likely to occur in the earlier pre-Cambrian time. It has not often occurred in post-Archean time, probably because the available heat in abyssal injections of this period has been too small to thin, and thus weaken, batholithic roofs sufficiently.

Lavas which reach the surface through the perforation of roofs by blow-piping gases (either juvenile or resurgent) are again of great variety of composition. Because of the conditions special to these 'central eruptions' at the earth's surface, the petrographic variety of rock types is here greater than it is in fissure eruptions or in intruded bodies. The cause of this contrast is chiefly found in the larger chance for magmatic differentiation in the main vents of central eruptions.

Genetic Classification of Magmas.

The magmas from which the igneous rocks have crystallized may be genetically classified as in the following list, which gives under each head a number of examples or rocks corresponding to the magma types.

1. *Primary basaltic magma* (primary in the sense that it has persisted in the molten or potentially molten state since the time of the oldest pre-Cambrian greenstones).
   Representative rocks: basaltic lava, gabbro, diabase, some basic porphyrites, etc.
2. *Primary granitic magma of the earth's acid crust.*
   Representative rocks: Perhaps none crystallized directly from this pre-Keewatin magma; indirectly represented in the acid granites of the pre-Cambrian batholiths.
3. *Direct magmatic differentiates of primary basalt.*
   Representative rocks: augite andesite, certain peridotites, anorthosite.
4. *Syntectic magmas.*
   A. Syntectics chiefly composed of primary basalt and primary acid earth-shell.
      Representative rocks: diorites, certain porphyrites, etc.
   B. Syntectics chiefly composed of primary basalt and sediments.
      Representative rocks: some hybrid types.
   C. Syntectics composed of primary basalt and essential amounts of both acid shell and sediments.
      Representative rocks: some hybrid types.
5. *Magmatic differentiates of syntectics of Class A.*
   Representative rocks: most granites; many aplites and lamprophyres.

6. *Magmatic differentiates of syntectics of Class B.*
    Representative rocks: abnormal granites (Moyie sills, Sudbury sheet, etc.); most nephelite and leucite rocks; some corundum-bearing types; essexite, etc.
7. *Magmatic differentiates of syntectics of Class C.*
    Representative rocks: granodiorite, dacite, some syenites, etc.
8. *Hybrid magmas formed by mixtures of two or more of the above-mentioned nine types.* (?)
    Representative rocks: (?)
9. *Transition magmas marking incomplete differentiation.*
    Representative rocks: 'intermediate' rocks of Moyie sills, Pigeon Point intrusive, Sudbury sheet, etc.; transition types in differentiated dikes, laccoliths, etc.

Application of the Theory to the Forty-ninth Parallel Rocks.

Introduction.—The assembling of old and new features in the general theory has been the product of the years of active field work on the Boundary section. It represents an attempt to find explanation for a multitude of new facts obtained during ten field seasons. At many points the reader has seen that this theory has already been tested for such bodies as the Okanagan composite batholith, the Purcell sills, the Bayonne batholith, and the stocks of the Selkirk range. Needless to say, the theory has not been brought to the present shape without abundant reference to igneous fields elsewhere. Neither the personal observations in the field, nor those described by other writers, have discovered facts which are irreconcilable with this general theory. Its strength is obviously due to its being a synthesis of many ideas from the leaders of petrological thought for the last two generations. The writer's principal contribution to it has been the negative one of showing a stumbling-block which has stood in the way of advance in theory. The leaders in modern petrology, for the most part, have denied the efficiency of magmatic assimilation *because they have generally failed to find hybrid rocks at molar and xenolith contacts.* The explanation of this patent fact is found in the stoping hypothesis. That hypothesis *demands* that hybrid rocks or direct evidence of assimilation shall normally fail at visible batholithic contacts. In making this failure an objection to the stoping hypothesis several writers have shown that they did not understand it fully. If stoping be accepted, abyssal assimilation on the large scale must be accepted, and mere differentiation of *original* magmas should no longer hold its entirely dominating place in petrogenic theory.

The explanation of facts which are intended to be covered by a theory do not suffice to prove that theory. It should do that as a matter of course. To be final it should take care of all new facts as they are discovered, and it should be prophetic of new findings in nature. The writer does not hold that the outlined theory has been sufficiently tested to be regarded as final. On the other hand, its ability to explain the hundreds of igneous bodies which occur in the Boundary section, as well as the thousands of other igneous bodies which he has studied elsewhere, either in the field or in the literature, gives the theory such cumulative sanction that it has been called a theory rather than a working hypothesis. The writer is emboldened to do this because the whole combination of principles is an eclectic summary of what appear to be the soundest views of petrologists in general.

Hence, in applying the theory to the Forty-ninth Parallel rocks, only a relatively small part of the proof of its validity is stated. The following paragraphs are thus meant for illustration and review rather than for demonstration. A multitude of field relations remain to be discovered before this, or any other eruptive area can prove the theory. Its exact application to many of the Boundary formations must await the results of future researches.

Evidence of a Primary Acid Earth-shell.—The postulate of a *primary acid shell* is supported by the petrographic analysis of the Priest River terrane and of the Rocky Mountain geosynclinal, the one pre-Cambrian entirely, the other partly pre-Cambrian. The Priest River terrane is, on the average, highly siliceous and it is probable that a minimum thickness of 6,000 feet of pure quartz is represented in the portion exposed within the Boundary belt. It will be remembered that neither bottom nor top of the Priest River series is exposed. The clastic beds of the Rocky Mountain geosynclinal represent from 10,000 to 20,000 feet of quartzose material, in which probably 10,000 feet of pure quartz are locally represented. Evidently a pre-Cambrian granitic or gneissic land of great extent must have furnished these sediments. Perhaps the Shuswap series of Dawson represents the now exposed equivalent of that ancient terrane.

The large areas of the pre-Cambrian demonstrated in the Cordillera, in eastern Canada, and elsewhere, are just such terranes, highly batholithic, which would furnish débris like that in the Priest River terrane and the Rocky Mountain geosynclinal clastics. Lawson and others have shown that visible pre-Cambrian batholiths were intruded and do not directly represent the original earth's crust, but calculation shows that the *material* of these batholiths was primary in the sense that it was not derived from quartzless rock through the leaching action of weathering (see page 702).

We conclude, therefore, that the lands whence the old quartzose sediments of the Boundary section were derived must have been either part of the original granitic crust or, more probably, the more or less remelted and recrystallized equivalent of that crust. The argument is enormously strengthened by the facts which are known concerning the pre-Cambrian sediments of eastern Canada, southern Appalachians, Sweden, Finland, China, Australia, etc.

Evidence of a Basaltic Substratum.—Among the evidences for the existence of a *primary basaltic substratum* we have noted: first, the fact that almost all the greater fissure-eruptions of the world are basaltic in composition; secondly, that basalt is the magma most persistently represented in igneous rock provinces; thirdly, the recurrence of eruptions of basaltic magma from the Keewatin time to the present, and; fourthly, that there is evidence of the direct derivation of voluminous andesites from basalt by differentiation within volcanic vents, thus increasing the known area where basaltic magma has been erupted.

1. Only one large field of fissure eruption is certainly represented in the Boundary belt, namely, that of the probably-Cambrian Purcell Lava. Though this rock is everywhere profoundly altered, its composition, throughout thousands of square miles, is basaltic, with a tendency in places to the (augite) andesitic. A very thin and quite local flow of liparitic lava is closely associated with the basaltic type at one point in the Purcell range. It is possibly the result of assimilation of acid rocks by the basalt, but its existence in no wise affects the statement that this fissure-eruption is essentially uniform and basaltic in composition. Nearly all of Paleozoic time, all of Mesozoic time, and much of Tertiary time elapsed before the vast Columbia lava-field was completed a short distance south of the Boundary Line. In that later and greater flood the lava varies from common olivine basalt to the more andesitic facies represented in the porphyritic, olivine-free phase of the Purcell Lava.* Calkins has pointed out the resemblance between this ancient porphyritic lava and an equally remarkable Miocene lava in Washington. The constancy of the type through so long a period is thus shown in details of structure as well as in the manner of its extrusion.

2. Basaltic magma is the only one known to have crystallized as visible bodies in each of the ranges between the Great Plains and the Pacific. With two exceptions, either the Purcell Lava or its approximate chemical equivalent, gabbro (rarely passing into diorite), form the only igneous masses seen where the Boundary belt crosses the Lewis, Clarke, Galton, MacDonald, McGillivray, Yahk and Moyie ranges. The first exception referred to is the liparite flow just mentioned. The other is the secondary granite of the Moyie sills. West of the Purcell Trench great abyssal injections (batholiths and stocks) first appear in the Boundary section, and it is west of the Purcell Trench that strong petrographic variety appears. The primary basalt never failed to be erupted in any of the ranges west of the trench, but many of its abyssal injections were so large as to furnish heat sufficient for much assimilation with consequent differentiation of non-basaltic rock bodies.

3. The many reappearances of basaltic magma as lavas or as injected masses is illustrated in the following chronological table, which embodies a partial list of the basic volcanic formations recognized by Dawson, G. O. Smith, and others, in regions close to the Forty-ninth Parallel.

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* See F. C. Calkins, Bull. 384, U.S. Geol. Survey, 1909, p. 51.

Period.	*Basalts, diabases or gabbros.*	*Augite (pyroxene) andesites.*
Pleistocene	Mt. Baker lava ?	Mt. Baker lava.
Post-Miocene........	Basalt dikes of Okanagan Range.	
Miocene	Yakima basalt of Washington.	Andesite of Wenatchee District (Washington).
Oligocene	Dawson's Upper Volcanic group of Interior Plateaus.	Porphyrite of Upper Volcanic group (Dawson).
	Basalt of Midway volcanic group.	Andesite of Midway volcanic group.
		Andesite of Skagit volcanic group
Eocene	Teanaway basalt of Washington.	
Mesozoic......	Basalts of Rossland, Beaver Mountain, and Phoenix groups.	Andesites of groups named in opposite column.
	Some gabbros of Columbia range.	
Jurassic	Rock Creek gabbro (age?)	
Triassic	Diabases of Nicola group (Dawson).	Porphyrites of Nicola group.
	Diabases of Vancouver group (Dawson).	Porphyrites of Vancouver group
Carboniferous................	Basalts of Chilliwack formation..	Andesite of Chilliwack formation.
	Basaltic traps of Hozomeen, Anarchist, and Cache Creek series (age?)	Andesitic traps of Hozomeen, Anarchist, and Cache Creek series (age?)
Cambrian (?)......	Purcell Lava.	
Beltian......................	Basalts of Irene Volcanic formation.	Andesites of Irene Volcanic formation.
Pre-Beltian......	Diabase of Dawson's Adams Lake series.	

4. The table also shows numerous examples of the common field-association of pyroxene andesite, or porphyrite, with basaltic rocks. The writer has assembled some of the facts which he regards as sufficient proofs of the derivation of this andesite from basalt, and has recently published a summary statement of the case.* In that paper emphasis was placed on a differentiation through the settling-out of ferromagnesian and cafemic crystals of early generation. But it was pointed out that a parallel effect might be produced by the settling-out of the same constituents in the liquid phase, that is, by a kind of liquation. Both actions comprise what has been called gravitative differentiation. Without, then, attempting to decide which process has been dominant in any case, we find in this general association of augite andesite with basalt along the Boundary Line, a substantiation of the hypothesis that the andesites have been derived from the more basic magma by gravitative differentiation. The complementary differentiates, the peridotites, are also found in close association with rocks of basaltic composition but, as to be expected, not so often nor in such volume as the andesites.

* R. A. Daly, Jour. Geol., Vol. 16, 1908, p. 401.

So great is the probability of this hypothesis that we may fairly regard the recurrences of augite andesite as so many recurrences of originally basaltic magma. The corresponding large addition to the number and size of the bodies which represent eruptions of basaltic magma, both in the Forty-ninth Parallel region and throughout the world, greatly limits the total volume of erupted magma which has not been either basaltic or granitic (or granodioritic) in composition. Perhaps less than one per cent of the world's eruptive magmatic bodies, reckoned as to their probable volumes, have had chemical compositions different from granitic, granodioritic, or basaltic magmas. In any case it is only a very small proportional volume of igneous rocks which need explanation as other than crystallized primary basalt, direct differentiates of primary basalt, or granitic differentiates.

Syntectics.—Since the primary acid shell is not exposed, the theory demands that besides primary basalt and its own differentiates all the other igneous rocks of the Boundary section are solidified *syntectics or solidified derivatives of syntectics.* This most difficult side of the theory's application has been approached at many points in the foregoing chapters. In the present summary only the more noteworthy considerations need again be mentioned.

There is an obvious preliminary step to be taken before a full discussion of assimilation is possible. For each magmatic body we should, ideally, know the composition of its country-rock on all contacts, roof, walls, and bottom—if there is a bottom. For stocks and batholiths we have little or no direct information concerning the nature of the walls for miles below the deepest valley which erosion has carved in the intrusive. If the roof is still largely preserved, the walls are effectively concealed. If erosion has removed the roof entirely, it may be impossible to know exactly of what rocks it consisted. Since stoping takes place on both walls and roof, the knowledge of the petrographic nature of both is essential to an understanding of the product of abyssal assimilation. In each case, the geologist can see only the uppermost part of a batholith, and, in general, he is compelled to regard his field observations as confined nearly to one level in that part. Only indirectly, therefore, can he get ideas as to the form and size of the body and as to the character of the *total* contact-surface on which stoping and marginal assimilation have held sway.

One of the principal data for the petrogenic discussion is thus often impossible of full attainment. It can only be found, even qualitatively, after a thorough field study of the invaded formation. Largely for lack of such observations a multitude of petrographic papers are almost useless to the student of petrogeny. Yet more serious is the error of many petrogenists who have decided on the magmatic happenings in batholiths and stocks simply from the chemical relations at visible contacts. This fundamental mistake has been made in the name of 'the scientific method,' which forbids 'speculation' and leaves the earth's interior 'to the poets,' but it is beginning to show its true character as a tradition which has done much to retard the advance of petrogeny for a generation.

Granting at once that we can secure only partial information as to the chemical nature of a batholith's country-rocks, it is still possible to believe that the known facts suffice to show extensive assimilation. The same considerations apply to those satellitic injections which are large enough and initially hot enough to be capable of some assimilation. In some cases the contacts of these injections are so exposed as to show all the important country-rocks; but then the igneous bodies must always be small affairs when compared to a first-class batholith.

The Granites.—Only two batholiths of true granite occur in the Boundary belt—the Rykert of the Selkirk range and the Cathedral of the Okanagan range.

The Rykert batholith makes visible intrusive contact only with the rocks of the Priest River terrane. From the field relations it seems probable that the contact at the roof was made with the same terrane. Beneath the terrane, which is the oldest exposed in the Boundary belt, is probably the usual acid pre-Cambrian complex. The assimilation of either the average Priest River rock or the postulated underlying formation by a great abyssal injection would, after gravitative differentiation, give an acid, granitic mass at the roof.

The Cathedral granite has replaced the Similkameen and Remmel granodiorites. The remelting of these might, by the theory, permit of a new differentiation whereby the salic elements collect at and near the batholithic roof in greater purity than was the case with the older magmatic chambers. The consanguinity of the Cathedral and Similkameen can only be explained on the view that such separation of the always 'antagonistic' salic and femic constituents did take place in the Cathedral magma chamber. This is, of course, no proof of the assimilation theory in the case. The theory is forced on us by the field evidence of replacement, and the generation of a younger, acid-alkaline granite is an incident of a very advanced differentiation of the syntectic.

The other true granites—the Sheppard granite in the Rossland and Bonnington mountain groups, the Bunker Hill granite, the Lost Creek granite and summit stocks of the Selkirks, the stock just east of Cascade, the Smelter granite at Grand Forks, and the Sumas granite at the Fraser river—are all cupola-like stocks probably satellitic to granodiorite batholiths. The more salic character of the stocks is again the result of more advanced differentiation, which was, perhaps, facilitated specially by the concentration of juvenile and resurgent gases in the cupolas. Nevertheless, the fact of replacement by these stocks is as indubitable as the replacement by the main batholiths.

The abnormal granites of the Moyie and Corn Creek sills have already been explained at length as due to assimilation of quartzose sediments by hornblende gabbro. (See pages 238 and 283).

The Granodiorites.—The granodiorite bodies are both larger and more numerous than those composed of true granites. The list includes the Bayonne, Trail, Cascade, Osoyoos, Similkameen, Remmel, and Chilliwack batholiths; many stocks in the Columbia mountain system, and the Castle Peak stock of the Hozomeen range. The whole series represents one narrow belt through the wonderful chain of granodiorite bodies which extends, with many breaks, from Patagonia to Western Alaska. Though batholiths of this chemical type are known in other continents, the home of the type and its greatest development is in the Cordilleras of the two Americas. The intrusive mechanism of the bodies is the same as that of the true granitic. The rather steady chemical contrast to the latter offers a petrogenic problem of special interest.

Several possibilities are open. These granodiorites may represent a less perfect differentiation of the same kind of syntectic as that from which the average post-Archean granite has been differentiated. Or, secondly, the average syntectics may be conceived as different in the two cases. Many true granites are known which have replaced little else than formations of granitic composition. In apparently all cases the typical granodiorite batholiths have been developed in folded geosynclinals carrying heavy masses of argillaceous rock, or in other terranes lower in silica than true granite. This is true of all the bodies in the foregoing list, as reference to the maps will show. It seems to be true of all the granodiorite batholiths of the Cordillera, as, for example, those of the Sierra Nevada, where huge volumes of Paleozoic and Mesozoic slates have been so evidently replaced. The assimilation of great volumes of argillite must affect the syntectics profoundly, and it is worth while to hold, as a good working hypothesis, that the granodiorite type is the product of a systematic differentiation of a syntectic which was formed not only of primary basalt and the pre-Cambrian granitic terrane but, also to an essential amount, of sediments, chiefly argillaceous.

The Diorites and Acid Andesites.—Four diorite bodies in the Boundary belt have merited special names; the Rock Creek, Lightning Creek, Slesse, and Sumas bodies (pages 392, 490, 532 and 527). All of these are small. The granodiorites often pass into quartz diorite, both at the Forty-ninth Parallel and throughout the Cordillera. The Boundary section illustrates also the worldwide association of diorite and true granite. A partial list of these associations may recall illustrations:—

Dioritic Rocks.	*Associated Granites and Granodiorites.*
Quartz diorite contact phase of Trail batholith.	Trail granodiorite, granitic facies; Sheppard alkaline granite.
Rock Creek diorite.	Rock Creek granodiorite.
Quartz diorite contact phase of Osoyoos batholith.	Granodiorite and granite (original phase?) of Osoyoos batholith.
Lightning Creek diorite.	Castle Peak granodiorite.
Slesse diorite.	Chilliwack granodiorite, granite.
Sumas diorite.	Sumas granite.

The general theory regards some dioritic rock as the typical crystallized syntectic formed by the assimilation of granite (generally pre-Cambrian) rock in primary basalt. That syntectic has generally been differentiated so as to afford new, secondary granites which, like the original material assimilated, are 'anchieutectics.' The failure of differentiation in the case of the diorites may be explained in at least two ways. The dioritic peripheral phases of many subjacent bodies seem to be best accounted for on the view that molar-contact chilling tends to increase viscosity beyond the point where magmatic splitting can take place (See page 772). Many diorite bodies, often slightly older than associated granites, are clearly satellitic injections, such as dikes, sheets, chonoliths, etc. Since these are all relatively small and quickly cooled bodies, it is readily understood that they will preserve the syntectic composition.

The diorites associated with granodiorites are subject to the same reasoning except that possibly they share with granodiorites certain chemical features due to the assimilation of basic sediments, or basic volcanic material, in addition to granitic rock. The known variability in the diorite family suffices to cover these complex syntectics as well as those formed of primary basalt and the earth's acid shell.

In the third place, the possibility is recognised that some rocks, fairly called diorites, may themselves be differentiates from special syntectics, or from the primary basaltic magma. Such types seem to be rare.

Most of the acid andesites are effusive equivalents of diorites and, on the theory, are to be regarded as similar syntectics, which, however, are generally somewhat differentiated. That the syntectics are here more differentiated is explained by the often favourable conditions for splitting in volcanic vents (pages 700 and 712). The dioritic magma gives granitic magma through splitting; andesitic magma gives liparitic (rhyolitic) magma through splitting. We can thus understand the common association of liparite and andesites in volcanic regions. The theory holds that some liparites may be extreme differentiates of the more basic augite-andesite magma, but typical post-Archean augite andesite is to be considered not as a syntectic but as a polar differentiate of basaltic magma.

This, in brief, is the writer's interpretation of the andesites occurring in the Irene, Beaver Mountain, Rossland, Phœnix, Midway, Pasayten, Skagit, and Chilliwack volcanic groups.

The Complementary Dikes and Sheets, and the Pegmatites.—The general theory includes the prevailing conception that these bodies are directly due to differentiation. They fall into groups according to their derivation from primary basaltic magma, from syntectics, or from differentiates of the basalt or the syntectics. The exact processes of the splitting are still largely mysterious. It seems probable that the differentiation is gravitative; the aplitic poles rising, the lamprophyric poles sinking in residual portions of magma. Since none of these bodies is ever large when compared to the parent batholiths, stocks, etc., and since the dikes regularly close batholithic periods, it is fair to conceive that the splitting magma was greatly reduced in volume from the size indicated in the batholith.

The necessary concentration of juvenile and resurgent fluids in the liquid magma remaining after most of a batholith has crystallized, may be the controlling condition. These volatile materials must lower the viscosity of the magma thus left in pockets or sheets within the frozen rock. In the specially fluid (though it be relatively cool) residual magma, extreme differentiation might take place, giving, for example, alaskite in the one pole, minette in the other, as the latest phases of granitic differentiation. On this view the complementary bodies must always be relatively small though they may be very numerous.

Their injection into the frozen portion of the batholith, or into its country-rocks, is often a mere hydrostatic process, perhaps aided by the expansive force and fluxing power of the gases, which are specially abundant in residual magmas. Harker's suggestion that the aplites are squeezed out is a valuable one. (See page 776). The pegmatites are of coarser grain than the aplites probably because the magmatic gases have been yet more concentrated in the pegmatite-filled fissures than in the fissures carrying the finer-grained complementary dikes.

The geology of the Forty-ninth Parallel seems to favour this hypothesis. A full display of complementary dikes is not often seen in the section. Most of those exposed are found in the Selkirk and Columbia ranges, where they are very abundant. The difficulty of discussing their origin is great because this region has been invaded by such different magmas as granodiorite, alkaline syenite, and monzonite. It is, therefore, often impossible to say which batholithic type has produced a given dike. In general, here as elsewhere, the minettes and kersantites seem to have been chiefly derived from granitic and granodioritic masses. Vogesite in one case at least, like the rare odinite, has been derived from granodiorite. (See page 348). Camptonite is usually associated with large alkaline intrusives, and the rule may apply in the Boundary section also, though the occurrences are too few to justify a more decisive conclusion. It has been noted that the peculiar 'olivine syenite' of the Selkirk and Columbia ranges possibly represents a minettic magma, which has crystallized with special coarseness because of the unusual size of the injections (see page 358).

The more acid complementary dikes are common and of the same character in the Boundary section that they have elsewhere. At several localities the alaskitic dikes are associated with stocks and other large intrusions of essentially similar composition. Examples are seen in the bodies of the Sheppard granite, which is chemically like the true aplites emanating from the Trail granodiorite. This suggests that the differentiation in batholithic cupolas is on the same principle as that postulated for complementary dikes.

The Abnormal Gabbros.—This division of the Forty-ninth Parallel rocks includes the staple types of the Purcell sills and dikes, and of the Basic Complex in the Okanagan range.

The argument of Chapter X. has been made without any necessary reference to the origin of the very peculiar gabbro of the Purcell injections. Its composition before it reached the visible chamber in the sedimentary series, offers a problem much more difficult than that of the granite layer in a Moyie sill. The chemical and mineralogical analyses shown on page 224 are typical of the many occurrences of the rock except where it has been plainly acidified by solution of quartzite. The chemical analysis is again stated in the following table, which also shows the average basalt, including diabase, etc., calculated from 198 analyses:—

	Purcell Gabbro.	Average Basalt.
SiO_2	51·92	49·06
TiO_2	·83	1·36
Al_2O_3	14·13	15·70
Fe_2O_3	2·97	5·38
FeO	6·92	6·37
MnO	·14	·31
MgO	8·22	6·17
CaO	11·53	8·95
Na_2O	1·38	3·11
K_2O	·47	1·52
H_2O	1·17	1·62
P_2O_5	·04	·45
CO_2	·06	....
	99·78	100·00

The gabbro is much the poorer in each of the alkalies. The microscope shows that nearly 60 per cent of the intrusive is composed of hornblende. The specific gravity of the freshest rock is 3·0 or over. There has evidently been a special concentration of cafemic material in the preparation of the magma. The result is a gabbro of peridotitic tendency. Apparently its origin cannot be stated in other than very doubtful terms. The relatively low total of the iron oxides and the high alumina do not favour the view that the gabbro is a direct basic differentiate of primary basalt. On the other hand, it is explicable as a syntectic composed of argillaceous and dolomitic sediments with primary basalt; or as a differentiate of such a syntectic. Needless to say, we have no data for testing this or any allied hypothesis. The only useful conclusion is that the abnormal gabbro does not lie outside the domain of the general theory.

The same statement may be made regarding the gabbroid complex of the Okanagan mountains. The petrogenic problem is there complicated by the intense dynamic (and perhaps thermal) metamorphism which has affected the complex.

The Alkaline Rocks.—There remains for brief discussion that group of igneous types which has long claimed the particular attention of petrographers,—the rocks rich in soda or potash, or in both alkalies. This richness is relative. Nephelite syenites usually carry more alkali than either granite or basalt. Monzonite is placed among the alkaline types because it contains a higher percentage of potash than rocks of the basaltic, gabbroid, or dioritic families, with which the monzonites may be compared as to silica percentage; all four types have nearly the same average content of soda.

Many, perhaps most petrologists have been of opinion that the alkaline rocks are products of primary reservoirs of alkaline magma. Rosenbusch's great system of classification has been soundly built on the basis of objective facts regarding the composition of igneous rocks; but he has coupled with his systematic statement a theoretical conception of rock origins which is at variance with the writer's general theory. The theory is evidently opposed to Rosenbusch's Kern hypothesis, or any other which postulates (post-Keewatin) primary magmas other than the basaltic. The writer is elsewhere presenting the evidence for the belief that the alkaline rocks are all more or less differentiated syntectics.* Their alkalies are regarded as having been derived from primary basalt; less often from masses of the earth's acid shell, which has been assimilated by primary basalt; or, in still less degree, from assimilated sediments. The principal cause for the special concentration of alkalies is found in the assimilation of limestones and dolomites, or other calcareous sediments. The solution of a few other types of rock may produce the same effect. Or, finally, it is conceivable that the addition of foreign gases to the magmatic solution may give the proper conditions for the concentration of alkalies in limited masses of rock.

This conclusion was first reached after an inductive study of the field association of nephelite syenite. It was found that, with very few exceptions, nephelite syenite and its effusive equivalent, phonolite, only occurred where subalkaline magma had cut important limestone or dolomite formations. In general, the original subalkaline magma was of basaltic composition. This is conceived to have been fluxed by the solution of the carbonate. The new lime or magnesia must fix silica to the extent of several times the weight of either base. The molecule thus formed is normally a pyroxene, which, with the likewise early-formed magnetite, olivine, etc., will tend to settle out of the magma. It is not essential to determine whether gravity acts before or after the actual crystallization of ferric, ferromagnesian, and cafemic components. The residual magma is necessarily higher in alkalies than the primary basalt. The fixing of silica by the new lime and magnesia means a desilication of the rest of the magma, and nephelite or leucite forms instead of feldspar. Since little alumina enters into the sunken components, this oxide may be in excess, and corundum will ultimately crystallize in the residual magma. Meanwhile, the carbon dioxide set free from the dissolved carbonate tends to rise through the magma. It may possibly carry with it soda and potash in combination as the alkaline carbonates. These familiar fluxes could rapidly enrich the upper part of a lava column with either or both alkalies and thus furnish a leucite basalt, a leucitite, or a nephelinite, from which the ferromagnesian and cafemic constituents of normal basalt have not had time to settle out. If the separation becomes perfect a phonolite or leucocratic nephelite syenite is the salic pole, while limburgites form the femic poles.

The hypothesis cannot be fully presented in this report but perhaps enough has been stated to show its nature. It explains the remarkably common association of alkaline rocks with calcareous and magnesian sediments; the desilication of primary magma, as indicated by the presence of nephelite and leucite in many alkaline types; the common supersaturation of alkaline magmas with alumina, resulting in the crystallization of corundum; the common occurrence of primary calcite, cancrinite, melanite, melilite, scapolite, wollastonite and

* Bull. Geol. Soc. Amer., Vol. 21, 1910, pp. 87-118.

diopsidic pyroxene in alkaline rocks; and the regular association of alkaline types with rocks of basaltic composition. The general conclusion is that all alkaline rocks are of secondary origin; their existence goes to strengthen belief in a primary basaltic substratum.

For the Boundary belt there are special difficulties in the way of applying tests to the hypothesis. The chief difficulty is the lack of sufficient exposure of the formations cut by the various alkaline bodies. This is, of course, no antecedent objection to the main principle, which remains as a good working hypothesis even if the field evidence at the Forty-ninth Parallel were nil. The following short review of field relations refers specially to the role played by limestone absorption in subalkaline magma, but it is to be understood that other sediments, or even basic crystalline rocks, may play a similar part. As pointed out in the general paper on this subject a relatively small proportion of dissolved carbonate may have great effect in the redistribution of chemical elements in a magma.

The most easterly of the alkaline terranes is the assemblage of latites and monzonitic intrusions at and near Rossland. These are intimately associated with basalts, augite andesites, and gabbros. The country-rocks include phyllite, greenstones, and serpentines, besides large bodies of Carboniferous limestone referred to the Pend D'Oreille group. That the limestone contacted with the magma at the Rossland vent or vents, is shown by its abundance in the fragments of the agglomerates on Sophie mountain and Sheep Creek valley. The Salmon River monzonite stock is partially surrounded by the very thick Pend D'Oreille limestone, though the two rocks do not show visible contacts.

There are few known bodies of typical syenite as large as the Coryell batholith, which is more than 100 square miles (about 225 square kilometres) in area. The general theory assumes that this batholithic mass is a differentiate from a large-scale syntectic. It must have lower silica than the average batholith—a granite—because of the enormous volume of basic volcanics, serpentines, argillite, and limestones, which the magma has so evidently replaced. Compared to granite the Coryell mass is somewhat desilicated. This desilication and the high alkalies are explained on the hypothesis now considered. The satellitic syenite porphyry is clearly a late salic differentiate from the main body.

The rhomb-porphyries and the shackanite of the Midway district are differentiates from one or more magmatic chambers not exposed. Their country-rocks are very seldom visible but in part at least have the same lithological character as those of the Rossland district. Heavy masses of limestone crop out at the few places where the Midway volcanics have been eroded off the Paleozoic formations.

The country-rocks of the Kruger alkaline body are also poorly exposed. On the west side they have been assimilated by the younger Similkameen batholith. On the east a small area remains, between the Kruger body and the Osoyoos granodiorite. South of the Boundary line the country-rock area broadens out, there showing an average lithological character identical with that of the Anarchist series.* This series, composed of argillite (phyllite), quartzite,

* Cf. G. O. Smith and F. C. Calkins, Bull. 235, U.S. Geol. Surv., 1904, p. 22 and Plate I.

and thick limestones, was invaded by the Kruger body. Whether or not the older ultra-basic intrusives, cutting the Anarchist series near Kruger mountain and visibly contacting with the alkaline body, were also significant factors in its genesis cannot be decided. There is clearly a chance that the heavy limestones in the Anarchist series were more important. The separation of the malignitic and foyaitic facies of the Kruger body is best explained as a differentiation in place.

In general, therefore, it may be said that the alkaline magmas of the Forty-ninth Parallel section all originated in regions of heavy sedimentation, and that thick limestones occur in the stratified series cut by the alkaline bodies. All these associations are new illustrations of a very general rule applying to the known occurrences of alkaline rocks. The rule is quite independent of any petrogenic theory. Its explanation through the syntectic-differentiation theory, whereby a genetic connection is found between the relatively rare alkaline rocks and the vastly more abundant subalkaline rocks, seems to be worthy of special attention.

APPENDIX A.

TABLE OF CHEMICAL ANALYSES.

The caption of each column bears the collection number of the specimen analyzed.

Numbers 295, 354, 392, 409, 456, 465, 493, 500, 509, 517, 528, 541, 543, 557, 666, 671, 836, 858, 900, 962, 1135, 1355, 1388, 1398, 1403, 1405, 1441, and the feldspar were analyzed by Mr. M. F. Connor, of the Canadian Department of Mines. He analyzed also No. 34, a specimen collected during the survey of the Rossland mining camp by Messrs. R. W. Brock and G. A. Young.

Numbers 7, 30, 54, 201, 282, 886, 1010, 1053, 1054, 1064, 1100, 1107, 1109, 1110, 1125, 1134, 1137, 1138, 1140, 1143, 1153, 1164, 1179, 1202, 1221, 1250, 1270, 1301, 1306, 1320, 1322, 1326, and 1338 were analyzed by Professor M. Dittrich of Heidelberg, Germany.

—	Purcell Mountain System.							Nelson Range.	
	Andesitic basalt, Purcell Lava.	Secondary granite, Moyie sill.	Secondary granite, Moyie sill.	Intermediate rock, Moyie sill.	Lower-contact phase, Moyie sill.	Usual type of gabbro, Purcell sills.	Hybrid rock, Purcell sills.	Gneissic granite, Rykert batholith.	Basic granodiorite, Bayonne batholith.
	1202	1137	1138	1140	1143	1153	1164	962	858
SiO_2........	41·50	71·69	72·42	52·63	52·94	51·92	54·02	70·78	60·27
TiO_2........	3·33	·59	·68	·62	·73	·83	1·95	·20	·63
Al_2O_3........	17·09	13·29	10·47	16·76	14·22	14·13	12·08	15·72	17·17
Fe_2O_3........	3·31	·83	·83	2·86	2·08	2·97	6·85	·36	2·36
FeO........	10·08	4·23	5·50	10·74	8·11	6·92	5·61	1·61	3.67
MnO........	tr.	·09	·16	·38	·35	·14	·09	·03	.14
MgO........	12·74	1·28	·41	4·33	6·99	8·22	2·82	·46	2·45
CaO	·97	1·66	2·53	6·17	10·92	11·53	14·63	1·92	6·49
SrO	.....	.....	.....	.....	.....	.....	tr.	tr.	·04
BaO	.....	.....	.....	.....	.....	.....	.....	·01	·04
Na_2O........	2·84	2·48	1·93	1·41	1·40	1·38	·60	3·48	2·92
K_2O........	·22	2·37	2·94	2·29	·49	·47	·14	5·23	3·25
H_2O-	·21	·14	·06	·12	·12	·10	·06	·10	·15
H_2O+........	6·99	1·31	1·11	1·17	1·56	1·07	·62	·25	·23
P_2O_5........	1·08	·07	·11	·33	·08	·04	·21	·26	·20
CO_2	none	·13	·61	·10	.....	·06	·19	.....	.....
	100·36	100·16	99·76	99·91	99·99	99·78	99·87	100·41	100·01
Sp. gr........	2·792	2·733	2·728	2·954	2·980	2·990	3·141	2·654	2·785
Page........	*209*	*229*	*230*	*232*	*234*	*224*	*245*	*287*	*291*

—	Rossland Mountains Chiefly.							
	Biotite granite, Sheppard stock.	Granodiorite, Trail batholith.	Monzonite ; facies of Coryell batholith.	Syenite porphyry, Rossland Mountains.	Basic olivine syenite.	Salmon River monzonite.	Rossland monzonite.	Augite-biotite latite, Rossland volcanics.
	500	509	517	409	354	671	34*	456
SiO_2	77·09	62·08	52·38	60·51	52·95	50·66	54·49	59·06
TiO_2	·05	·73	1·10	·60	·70	1·32	·70	1·08
Al_2O_3	13·04	16·61	15·29	16·71	14·00	16·91	16·51	16·24
Fe_2O_3	·82	1·53	2·99	1·72	2·57	1·71	2·79	·43
FeO	·26	3·72	5·53	3·34	5·55	6·17	5·20	4·88
MnO	tr.	·11	·10	·10	·13	·16	·10	·20
MgO	·12	2·44	5·84	2·53	7·29	5·50	3·55	3·51
CaO	·63	5·20	7·30	3·62	6·93	8·26	7·06	5·59
SrO	none	·03	·15	·12	·11	·08	....	·12
BaO	none	·09	·25	·10	·32	·23	....	·11
Na_2O	3·11	3·18	3·68	4·64	2·73	2·89	3·50	2·84
K_2O	4·50	3·29	3·84	5·20	5·09	4·45	4·36	3·95
$H_2O -$	·03	·16	·21	·03	·16	·14	·07	·21
$H_2O +$	·07	1·00	·63	·27	·50	1·06	1·18	·19
P_2O_5	·10	·30	·75	·16	·47	·91	·20	·21
S	....	....	....	....	....	....	·23	....
CO_2	....	....	....	....	....	....	·10	·70
	99·82	100·47	100·04	99·65	99·50	100·45	100·04	99·32
Sp. gr.	2·600	2·754	2·847	2·667	2·872	2·843	?	2·796
Page	*355*	*347*	*361*	*364*	*357*	*305*	*343*	*327*

* Analysis furnished by Mr. R. W. Brock.

—	Rossland Mountains Chiefly.								
	Augite-olivine latite, Rossland volcanics.	Augite latite, Rossland volcanics.	Hornblende-augite latite, Rossland volcanics.	Missourite dike.	Hornblende-augite minette dike.	Kersantite dike, Nelson range.	Olivine-augite minette dike, Nelson range.	Augite minette dike. Nelson range.	Harzburgite, Rossland Mountains.
	465	543	557	541	493	666	836	900	392
SiO_2	58·67	54·54	52·17	42·31	53·68	47·42	48·33	53·32	42·99
TiO_2	1·00	·96	·80	2·00	·90	·70	·81	·90	tr.
Al_2O_3	15·67	18·10	16·59	11·40	16·89	15·65	12·56	14·16	1·11
Fe_2O_3	2·85	1·14	8·32	4·07	1·28	2·66	1·87	2·15	1·87
FeO	3·28	4·63	not det.	6·11	5·53	4·05	5·26	5·08	5·91
MnO	·11	·10	·11	·11	·11	·10	·13	·10	·05
MgO	3·86	4·56	3·87	11.31	3·70	4·90	9·07	7·90	43·14
CaO	5·33	5·85	8·25	11·02	6·08	8·56	8·94	7·12	·10
SrO	·09	·15	·05	·16	·10	·10	·05	·05	none
BaO	·11	·21	·15	·64	·38	·14	·24	·12	none
Na_2O	4·77	3·38	3·91	·82	4·03	2·60	1·81	2·39	·29
K_2O	3·08	5·44	4·00	3·69	4·32	4·10	4·67	4·80	·13
H_2O-	·02	·10	·13	2·28	·10	·30	·97	·26	·51
H_2O+	·54	·50	1·17	2·72	1·85	2·60	2·63	1·24	4·00
P_2O_5	·16	·46	·24	1·44	1·05	·54	·78	·66	·04
Cr_2O_3	....	....	....	·05	....	....	....	....	....
CO_2	....	....	·56	tr.	....	6·24	2·64	....	....
NiO	....	....	....	....	....	....	....	....	·15
S	....	....	1·37	....	....	....	....	....	....
	99·54	100·12	101·69	100·13	100·00	100·66	100·76	100·25	100·29
Sp. gr	2·751	2·745	2·852	2·817	2·723	2·740	2·771	2·831	3·075
Page	*328*	*325*	*329*	*368*	*310*	*313*	*311*	*307*	*336*

	Rossland Mountains	Midway Mountains Chiefly.					Okanagan Range.		
—	Dunite.	Altered dunite at Rock creek.	Pulaskite porphyry.	Rhomb-porphyry, Rock Creek chonolith.	Rhomb-porphyry, Rock Creek chonolith.	"Shackanite", lava flow.	Malignite, Kruger alkaline body.	Nephelite syenite, Kruger alkaline body.	Nephelite syenite, Kruger alkaline body.
	528	282	1010	1053	1054	1064	1100	1109	1110
SiO_2	41·36	40·25	62·04	52·43	51·83	52·24	50·49	55·11	52·53
TiO_2	none	tr.	·72	·86	·86	·73	·92	·48	·07*
Al_2O_3	1·21	1·10	17·63	19·18	18·25	19·28	15·83	21·28	19·05
Fe_2O_3	9·18	4·61	1·98	3·51	4·26	4·34	6·11	2·64	4·77
FeO	not det.	3·04	1·57	2·08	1·46	1·13	3·04	1·29	2·10
MnO	·10	·11	tr.	tr.	tr.	tr.	·11	·08	·13
MgO	42·90	37·91	·99	2·61	3·28	1·85	3·38	·59	1·99
CaO	1·34	1·16	1·75	3·71	4·08	4·43	7·99	2·82	5·75
SrO	none	....	......	·42	·42	·42	....	....	·19
BaO	none	....	....	·35	·43	·36	....	....	·09
Na_2O	·04	·48	4·73	4·85	4·68	6·34	3·12	6·24	4·03
K_2O	·04	·16	6·74	5·95	5·75	2·40	6·86	8·36	7·30
H_2O-	·16	·32	·12	·27	·27	·80	·29	·14	·13
H_2O+	1·94	9·08	1·18	3·19	3·15	4·63	1·20	·58	1·49
P_2O_5	·04	....	·17	·42	·55	·59	·42	·27	·28
Cr_2O_3	·15	·15	.....	....	....	....	....	....	....
CO_2	1·40	1·95	·20	tr.	·43	·35	·07	·08	·27
NiO	·15	....	......	....	....	....	....	....	....
S	·50	....	.....	....	....	....	....	....	....
	100·51	100·32	99·82	99·83	99·70	99·89	99·83	99·96	100·17
Sp. gr.	3·160	2·868	2·497	2·608	2·621	2·528	2·849	2·666	2·719
Page	*335*	*394*	*419*	*409*	*405*	*414*	*450*	*453*	*451*

* Includes ZrO_2.

	Okanagan Range.								Skagit Range.
	Crushed granodiorite, Osoyoos batholith.	Gneissic biotite granite: Eastern phase of Remmel batholith.	Basic granodiorite: Western phase of Remmel batholith.	Monzonitic phase of Similkameen batholith.	Granodiorite, Similkameen batholith.	Granodiorite, Castle Peak stock.	Biotite granite, Cathedral batholith.	Ashnola gabbro.	Slesse diorite.
	295	1398	1405	1107	1355	1441	1388	1403	54
SiO_2	68·43	70·91	63·30	54·06	66·55	66·55	71·21	47·76	56·90
TiO_2	·20	·20	·50	·80	·40	·60	·16	2·20	·84
Al_2O_3	15·80	16·18	17·64	18·75	16·21	15·79	15·38	18·58	18·17
Fe_2O_3	1·06	·51	1·58	4·64	1·98	·15	·25	2·19	1·23
FeO	1·85	1·09	3·08	3·10	1·80	3·08	1·47	9·39	5·88
MnO	·10	·04	·47	tr.	·12	·06	·06	·29	·21
MgO	1·46	·37	1·23	2·75	1·32	2·14	·33	4·15	4·36
CaO	4·08	2·92	5·03	7·35	3·86	3·47	1·37	9·39	6·51
SrO	·02	....	none	....	·01	·01	none	·03	·18
BaO	·09	·10	·05	....	·03	·03	·09	·02	....
Na_2O	3·47	1·33	4·56	4·60	4·07	4·39	4·28	3·61	3·23
K_2O	2·51	5·53	1·16	3·00	2·84	2·80	4·85	·47	1·57
H_2O-	·05	·03	·14	·10	·01	·05	·02	·12	·12
H_2O+	·53	·12	·51	·41	·24	·40	·43	·53	·77
P_2O_5	·07	·11	·27	·55	·15	·04	·05	·78	·10
CO_2	....	....	....	·11	....	....	....	....	·08
	99·72	99·44	99·52	100·22	99·59	99·56	99·95	99·51	100·15
Sp. gr.	2·708	2·654	2·721	2·819	2·693	2·678	2·621	2·957	2·793
Page	*440*	*446*	*444*	*457*	*456*	*493*	*460*	*435*	*533*

—	Skagit Range.			Rocky Mountain System.					
	Quartz diorite, phase of Chilliwack batholith.	Soda granite, phase of Chilliwack batholith.	Sumas granite.	Orthoclase-bearing dolomite, Waterton formation.	Silicious dolomite, middle Altyn, Clarke range.	Silicious dolomite, lower Altyn, Clarke range.	Silicious dolomite, upper Altyn, Clarke range.	Silicious dolomite, upper Altyn, MacDonald range.	Silicious magnesian limestone, Siyeh, Clarke range.
	7	30	201	1338	1320	1322	1326	1270	1306
SiO_2	60·36	71·41	71·24	30·46	18·89	13·46	25·50	26·07	35·58
TiO_2	·70	·34	·42	....	....	....	....	....	....
Al_2O_3	17·23	14·38	14·11	6·86	·49	1·56	2·25	3·92	3·40
Fe_2O_3	1·93	1·33	1·75	4·53	·72	1·05	·62	2·08	1·56
FeO	3·74	1·17	1·23	1·89	....	·48	·38	2·68	0·87
MnO	·14	·04	tr.	....	....	....	....	....	....
MgO	3·66	1·13	1·07	10·07	16·79	17·81	14·77	12·99	10·09
CaO	6·07	2·51	2·87	16·02	23·86	25·08	21·65	19·58	19·72
SrO	....	....	....	....	....	....	....	....	....
BaO	....	·03	·09	....	....	....	....	....	....
Na_2O	3·58	4·12	2·37	·87	·47	·28	·86	1·04	0·51
K_2O	1·74	2·97	3·97	5·71	·57	1·08	1·27	1·40	1·21
H_2O-	·06	·09	·11	·11	·18	·04	·12	·04	·17
H_2O+	·55	·30	·59	1·31	1·57	1·23	·42	1·52	2·93
P_2O_5	·11	·13	·17	....	....	....	....	....	....
C	....	....	....	....	....	....	....	....	·03
CO_2	·08	·12	·28	22·55	36·89	38·08	32·03	29·14	23·80
	99·95	100·07	100·27	100·38	100·43	100·15	99·87	100·46	99·87
Sp. gr	2·757	2·653	2·651	2·749	2·802	2·805	2·768	2·816	2·741
Page	*536*	*537*	*527*	*53*	*60*	*58*	*61*	*99*	*75*

—	Rocky Mt. System.			Purcell Mountain System.				Nelson Range.	
	Silicious magnesian limestone, Siyeh, Galton range.	Silicious dolomite, Sheppard, Clarke range.	Calcareous argillite, MacDonald formation.	Calcareous metargillite, Eastern phase of Creston formation.	Quartzite, Western phase of Creston formation.	Quartzite, Western phase of Kitchener formation.	Contact-metamorphosed Kitchener quartzite.	Dolomite, Priest River terrane.	Rhomb-feldspar from Rock Creek chonolith.
	1221*	1301	1250	1179	1125	1135	1134	886	—
SiO_2	36·80	24·61	68·37	51·65	82·10	76·90	74·23	5·84	54·60
TiO_2	......	......	......	......	·40	·35	·58	......	·60
Al_2O_3	5·92	6·84	7·02	7·85	8·86	11·25	13·23	·80	22·17
Fe_2O_3	1·40	·58	4·41	1·74	·49	·69	·84	·79	2·00
FeO	·85	2·01	3·99	·98	1·38	3·04	2·65	·16	not det.
MnO	......	......	......	......	·03	·02	·07	......	tr.
MgO	6·38	13·34	4·41	3·67	·56	1·01	1·02	19·38	1·30
CaO	21·03	19·14	3·89	15·02	·82	·88	1·13	28·31	4·62
SrO	......	......	......	......	......	......	tr.	......	·80
BaO	......	......	......	......	......	......	......	......	1·09
Na_2O	·76	·62	·87	2·69	2·51	3·28	2·78	·27	4·46
K_2O	1·68	2·07	1·34	1·38	2·41	1·36	2·66	·09	5·58
H_2O-	23	·24	·25	·09	·05	·20	·08	·03 }	2·50†
H_2O+	2·49	1·76	3·60	1·81	·37	1·20	·81	·63 }	
P_2O_5	......	......	......	......	·04	·15	......	......	......
C	·08	......	......	......	......	......	......	......	......
CO_2	22·71	28·89	1·91	13·05	......	tr.	·08	43·55	tr.
	100·33	100·10	100·06	99·93	100·02	100·33	100·16	99·85	99·72
Sp. gr.	2·748	2·779	2·687	2·654	2·681	2·680	2·722	2·822	—
Page	*106*	*78*	*102*	*127*	*125*	*130*	*241*	*262*	*403*

* Mean of two analyses. † At 90° C. ·17% water given off.

APPENDIX B.

A REPORT ON FOSSIL PLANTS FROM THE INTERNATIONAL BOUNDARY SURVEY FOR 1902-05, COLLECTED BY DR. R. A. DALY.*

By D. P. Penhallow, D.Sc., F.G.S.A.

In the spring of 1903 I received from Dr. R. A. Daly, of the Department of the Interior, a small collection of plants from the region of the International Boundary in British Columbia, as derived from a rapid reconnaissance (in 1902). This material was reported upon tentatively in May of the same year, and though much of it was of such an imperfect nature as to render final conclusions impossible, it was nevertheless of a very suggestive character, and it not only yielded some new species, but it permitted of provisional conclusions as to the ages of the several deposits represented.

In the autumn of 1905, Dr. Daly forwarded to me a larger collection, embracing material of a much more definite character, and derived not only from the same, but from other localities in the same general region. This material was found to confirm many of the provisional conclusions derived from the previous collection; to add several new species to our knowledge of the flora of that section, and to afford very definite information as to the age of the deposits. It is thus found to be desirable to combine these two collections in the present report. As all the specimens were designated by numbers representative of special localities, these numbers may be used in the present instance for convenience of reference; but the individual specimens of each group will also be further designated by the use of subordinate letters or numbers which will be found upon the label of each specimen described, and in this way the identity may be fully established, and reference to the type facilitated.

General Description of the Material and its Source.

No. 250 of 1903 and 1905.†—The two collections under this number represent identical localities. Dr. Daly states that they were obtained from a shallow gulch east of a bridge over Kettle river, six miles up the stream from the town of Midway. 'The formation is a series of gray sandstone layers; this is one of the isolated patches of so-called Tertiary noted by Dawson in his description of the interior of British Columbia,' and on the map of the Geological Survey

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* Read before the Royal Society of Canada, May 15, 1907, and printed in its Transactions, Section IV, 1907, pp. 287-334.

† The collection made in 1902 was forwarded to Professor Penhallow in 1903 and is here referred to as the "1903" collection.

it is marked as of Miocene age. 'It is cut by basaltic and andesitic dikes, and is overlain by flows and tuffs of the same eruptive material. The general dip is 35 degrees to the southeast, but in the lower part of the gulch it rises to 75 degrees in the same direction. The whole group of sandstones and lavas has been faulted and folded.'

The specimens from the first collection embraced various fragments of leaves in a very imperfect state of preservation, from which no very definite conclusions could be drawn. There were also two specimens of calcified wood which were found to be new. In 1905, the collections were found to include fragments of fruit, leaves and stems of limited value; but they were chiefly remarkable for the large number of calcified fragments of wood, most of which showed a fine state of preservation. Two of these proved to be identical with previously recognized species, while two were entirely new.

Numbers 1001 and 1007 of the 1905 collection are reported by Dr. Daly as having been collected on the Kettle river, a few miles north of the International Boundary, and from a locality near to No. 250. In all three of these cases the general formation and the character of the specimens show clearly that they are of the same age.

Number 271 of the 1903 collection represents the north side of the cañon wall of Rock Creek, an affluent of the Kettle river, about six miles west of No. 250, and, therefore, within an area usually designated as Miocene; and according to Dr. Daly, the rocks are undoubtedly of the same age as those of No. 250. They consist of gray sandstones, freestones and light and dark gray, papery shales. The dip is 20 degrees due north. These beds overlie a coarse conglomerate which is associated with coarse arkose overlying its parent rock, a coarse granite. They are cut by basic dikes and by a laccolith-like mass of porphyry. The very few specimens obtained from this locality are all undoubtedly of rather recent age, and in their general character they tend to confirm the relations otherwise indicated as existing between them and Nos. 250, 1001 and 1007. The state of preservation is nevertheless very poor, and they give very little reliable information as to the precise nature of the species.

Previous collections from British Columbia have shown the existence there of Tertiary plants, and in particular, Sir William Dawson described a number of specimens from the Similkameen valley which he assigned to the Upper Eocene (10). As the locality is in somewhat close proximity (about sixty miles west) to the one under discussion, it is possible that they are of the same horizon, and they must therefore be considered together in future discussions.

Number 1433 of the 1905 collections embraces a number of fragments of leaves and stems of an undeterminable character, and while they fall within the same general region as 1430-1436, and are presumably of the same age, they offer no reliable evidence to this effect.

Number 1430 of the 1905 collection is by far the most important numerically, as well as with respect to the number of recognizable species. These specimens not only include previously described species, but they also present several new ones, and on the whole, they constitute the keynote for the four related localities.

Numbers 1428, 1430, 1433 and 1436 of the 1905 collections were taken from a large area of what has always been regarded as Lower Cretaceous, occurring at the Boundary (49th parallel) Line, at a point between the Pasayten and Skagit rivers, within an area which is indicated on the Geological map as Cretaceous. 'There seem to be at least 28,000 feet of this series altogether, and it appears to correlate with the Shasta-Chico Series.' An important aspect of Nos. 1428 and 1430 is to be found in their relative ages as well as to whether they are really Cretaceous. In this connection Dr. Daly observes that 'the beds bounding them dip under ammonite-bearing beds of Cretaceous age, but it is possible that they are younger and have been faulted down into that attitude.'

1428 is a locality of exceptional interest, since it has yielded some of the most perfectly preserved specimens of the entire collection, and it embraces at least one new species of fern which has great value as an index of geological age. There are also a number of poorly preserved forms which, by comparison with determinable ones, may be correlated with certain doubtful forms observed in the collection of 1903, with respect to which the provisional conclusions formerly reached are now fully confirmed.

1436 also represents fragments of stems or leaves of a very doubtful character, but again, by comparison, it is possible to correlate them with recognized species.

Number 471 of the 1903 collection 'comes from a series of black, shaly beds, associated with sandy strata, dipping 35 degrees due east on the eastern slope of Sheep Creek valley just southeast of Rossland. The fossils came out of bands immediately above the Red Mountain railroad track. The whole series seems to be made up of assorted (water-laid) ash beds and tuffaceous deposits. These are overlain by coarse agglomerates, which compose much of the great volcanic group of rocks surrounding Rossland, and in which the copper-gold ores are largely found.'

Locality 471 is about one hundred and twenty miles east of 1428 and 1436, being near Rossland, while the latter are on the summit of the Cascade mountains. The specimens from 471 consist entirely of a number of pyritized fragments of leaves which show little evidence that can be utilized for purposes of identification. The locality is an entirely isolated one, but by close comparison of the specimens with those from the more western localities, it is possible to draw the conclusion that there is essential identity with specimens from 1428, and that 1428, 1430, 1433, 1436 and 471 are all of the same age, questions of the precise horizon within these limits to be determined in the following discussion.

A review of all the material embraced in the two collections, shows that it falls into two well defined periods—Cretaceous and Tertiary, and it is most gratifying to find in this connection that the tentative conclusions based upon the very imperfect material of the 1903 collection have been fully sustained by our later studies.

DESCRIPTION OF THE SPECIMENS

TERTIARY.

$\frac{2 \text{ \& 1a.}}{250}$ PICEA COLUMBIENSIS, n. sp.

This plant is represented by two parts—fragments of stems and cones. The cone $\frac{(250)}{2}$ is represented by a single, but beautifully preserved cast (Plate I), from which the following characters may be drawn:—

Cone narrowly ovate or conical, 2·3 x 5 cm.; the scales 0·6 x 1·1 cm. the margins conspicuously but finely dentate.

The fragments of stem are obviously from the terminal portions of branches of some coniferous trees, and from the character of the leaf scars, they are to be referred to the genus Picea. While these branches are not connected with the cones in any way, nor do they even occur in the same blocks of matrix, nevertheless they are from the same beds, and in the absence of any other representative of the genus, it is probably justifiable to conclude that they are of the same species and will be so considered.

The plant here represented has no living relative with which it may be compared, but the general aspect and structure of the cone would seem to place it without doubt, among the red spruces to the cones of which it bears a strong resemblance with respect to general form and the character of the scales, though the dentate margins of the latter at first suggest affinity with P. nigra.

Among the fossil representatives of this genus, all the recognized species are of Tertiary age and very few in number. The majority are known through their wood and have been derived from the Pleistocene, but Knowlton (33) has described a species from Kukak Bay, Alaska, under the name of P. harrimani. This is the only North American species which has so far been recognized through its cones only, and an inspection of the figures given shows it to be of a totally different type, approximating, according to Dr. Knowlton, to the existing Alaska spruce—P. sitchensis. The age of this tree is given as Upper Eocene.

$\frac{250}{\text{1b. \& 3b,}}$ $\frac{1007}{\text{4, 6b.}}$ of 1905. CYPERACITES HAYDENII, Lesq.

This species is one of those problematical forms, concerning which it seems extremely difficult to obtain sufficiently comprehensive data to admit of a fully reliable diagnosis which will establish its character beyond doubt. All the specimens so far figured, represent fragments only, and so poorly preserved as to make adequate description impossible. So far as may be judged from the figures given at various times, as well as the material which has passed through my hands, the leaf seems to have been a somewhat delicate one, in consequence of which the essential characters have been but poorly preserved. That it was a monocotyledon of some sort is quite evident, but it will not be possible to place it more exactly until more perfect material is found, and the name commonly assigned on the basis of Lesquereux's original determination must be viewed as wholly provisional.

As presented to us in the present collections, this plant appears from two different localities, although representing the same geological horizon—250 and 1007. The specimens show the plant in somewhat different conditions of preservation, but with a certain constancy of characters which permit of coordination. They are always more or less distinctly rugose, sometimes also with transverse wrinkles. They sometimes appear without any evidence of venation, while in other instances they show a pronounced indication of a strong, central nerve or midrib. They are among the forms which are entirely new to the region under consideration, but they are recognized components of the Green River Group of Randolph's County, Colorado (**42**).

The specimens now in hand are fragments 8-9 cm. long and 2·6 cm. wide; much altered by decay, but showing imperfectly, a rather fine, parallel venation and marked evidences of a strong, central midrib which, however, is not infrequently wanting in the narrower specimens. There is also, frequently, a strong transverse wrinkling due to longitudinal displacement.

Our specimens present a somewhat strong resemblance to the somewhat recently described Anomalophyllites bridgetonensis of Hollick, from the Yellow Gravels of Miocene age at Bridgeton, N.J. (**32**). This is a problematical form which Dr. Hollick has referred to Anomalophyllites as probably representing its nearest affinity, but it is difficult for me to make any precise distinction between it and Cyperacites according to the accepted definition of that genus. As a provisional reference, perhaps it is of little consequence which genus is given the preference. Our material seems to differ from Hollick's A. bridgetonensis in being much narrower, and in having a much shorter and more slender petiole, differences which are specific rather than generic, while they may also, possibly, represent accidental differences in imperfectly preserved material.

$\frac{250}{2, 5, 11.}$ & $\frac{271}{1, 2, 7.}$ of 1903.

A number of poorly preserved fragments of leaves, the exceedingly fragmentary condition and imperfect structural markings of which make specific reference of doubtful value. But provisionally, at least, it would seem that they must be assigned to Cyperacites.

$\frac{250}{3}$ of 1905.

The specimens included under this number are exceedingly problematical. They represent fragments of endogenous leaves which are not complete either as to their length or breadth, base or apex. It is, therefore, impossible to reach final conclusions respecting them. They show, however, a parallel venation, a regular plication (?) or series of rounded ridges distant at rather regular intervals of 4 mm. No other structural details are recognizable. Precisely the same plant appeared in the collection of 1903 under the number $\frac{250.}{1, 5}$ The external appearance of these remains at once suggests the structure of Calamites radiatus of Heer, but there are two very substantial objections to considering the existence of such a relationship, because (1) it has not been possible to determine the presence of the characteristic joints of that species, although certain lines of fracture due to longitudinal compression, have suggested to some observers to whose attention they were directed, their identity with such joints; and (2) Calamites radiatus is a Carboniferous type, with which it would be impossible to correlate our present specimens, which are unquestionably of more recent origin. There is, likewise, no point of comparison with Heer's Caulinites, which is of Mesozoic age, nor with any of the various species of Sabal, which have been described as occurring in the Cretaceous and Tertiary. Under these circumstances, it seems altogether probable that the various ridges are not original features of the organ, but that they have been produced by certain conditions of preservation, and that their regular occurrence at stated intervals is only an expression of the location of the principal nerves or veins. On the basis of this interpretation we must conclude that these fragments cannot be definitely separated from those representing Cyperacites haydenii, with which they must therefore be regarded as identical. This conclusion also gains strength from the circumstance that specimens $\frac{271}{1,2,3}$ present intermediate forms of such a character as to readily show how the one passes into the other by varying conditions of preservation.

$\frac{250}{4,10}$ of 1903 and $\frac{271}{3}$ (= $\frac{250}{3}$ of the previous report incorrectly given).

Cyperacites, sp.

Various fragments of an endogenous leaf, which it has been customary to refer to the genus Cyperacites without any specific designation, because the details of form and structure are usually so altered as to make identification impossible. No. 4, nevertheless, shows the details of the venation much more perfectly than is commonly the case. The whole fragment is 1.5 cm. broad and 8.2 cm. long. The very prominent and parallel venation is found to show about 9 veins to the cm., but this is only approximate, since it is found that owing to a collapse of the general structure, some veins are much nearer than others. Their normal interval would seem to be about 1 mm. In specimens $\frac{1007}{3a. \& 6a}$, precisely the same forms recur, and they must be held to fall under the same generic designation.

Remains of this character are of very common occurrence throughout the Tertiary, and Dawson (**5**) has even recorded under this name, a specimen which he describes as 'A slender, grass-like stem with linear, finely striate leaves, alternately disposed and not proceeding from enlarged joints.' In his account of the Flora of the John Day Basin in Oregon, the horizon of which is regarded as Upper Miocene, Knowlton (**34**) records the occurrence of a stem showing parallel venation, the whole specimen corresponding in all its details to that which has been described from the 1903 collection under number $\frac{271}{3}$.

$\frac{250}{7}$ of 1903 (= $\frac{271}{7}$ as previously reported under wrong number).

These specimens embrace, in addition to fragments of Cyperacites haydenii, as already discussed, one fragment of a Cyperacites of unknown species, which must be referred provisionally to the group embraced in $\frac{250}{4, 10}$ etc. In addition there are a large number of fragments of seeds and leaves of an undeterminable character, but which may belong here.

$\frac{250}{8}$ of 1903. UNDETERMINABLE.

Two fragments of small stems or leaves, a few cm. long by a few mm. wide. There is no evidence whatever of structure, and it is impossible to satisfactorily correlate them with any known forms.

$\frac{250}{8}$ of 1903. FERN STIPES.

A single specimen, representing a portion of a branching stem which exhibits no detailed structural features, but has all the external aspects of a portion of a fern stipe bearing the basal portion of the rachis of one of the pinnæ. As such, the specimen has no stratigraphical value, since the species or genus cannot be determined; but it is highly probable that it is identical with $\frac{271}{4}$ of the same collection, which represents fragments of stems only two or three centimetres long, mingled with fragments of leaves.

$\frac{250}{c}$ of 1905. BETULA, sp.

Under this number are included isolated specimens about 1 cm. long by 0·5 cm. wide, evidently the remains of a fruit of some sort. A careful inspection shows it to be made up of a series of closely packed scales which make it an oblong cone closely comparable with the cone of Betula, to which it is provisionally referred.

$\frac{250}{a, b}$ of 1903. PINUS COLUMBIANA, n. sp.

Among the collections of 1903 were two fragments of calcified wood, both of which represent the same species. The larger specimen was a fragment of a good sized but flattened branch, measuring about 10 cm. in length, 9 cm. in breadth and 2·8 cm. in thickness. The structure was well preserved and admitted of determination without much difficulty, although decay and alteration by crushing had obliterated and destroyed some of the structural features. There was no difficulty in recognizing the wood as representative of a hard pine, but it was impossible to identify it with any previously recognized fossil type, or with any existing species, although it is of interest to find that it is a hard pine of the general type of P. glabra, to which it somewhat closely approximates, but from which it differs materially in the structure of the medullary ray. In the collections of 1905, from the same locality, precisely the same wood was once more brought under my notice, being recognized under the designation $\frac{250}{J}$. This more recent material, however, has been found to be in a much better state of preservation, conditions of decay not having progressed so far as in the previous case, and it therefore served to complete the diagnosis with respect to several important characters which were either wholly wanting in the previous material, or imperfectly presented.

There is no record of the wood of Pinus having been found in the same horizon in North America, though Knowlton has described two species from the Laramie of the Yellowstone National Park, under the names of Pityoxylon aldersoni and P. amethystinum (**35**). Between these and the present specimens, however, there are no points of resemblance. The diagnosis for the present species is as follows:—

PINUS COLUMBIANA, n. sp.

Plates III and IV.

Transverse.—Growth rings variable though generally very broad in the large stems. Spring wood usually predominant, the transition to the summer wood gradual, but in the narrow rings more or less abrupt and sometimes conspicuously so; the tracheids large, thick-walled and often conspicuously so, definitely rounded, often radially oval, chiefly uniform, more or less equal, in regular radial rows. Summer wood conspicuous, dense and often thin. The structure as a whole is that of a rather dense wood of medium hardness. Medullary rays prominent, not very numerous, resinous and distant upwards of 9 or more rarely 15 rows of tracheids. Resin passages conspicuous, rather large and scattering throughout the growth ring, the parenchyma cells large, thin-walled and in two rows, or forming large, irregular tracts upwards of 6-9 tracheids wide; resinous; thyloses not obvious.

Radial.—Medullary rays resinous; the tracheids rather numerous, marginal and interspersed, not obviously predominant, very variable and often as high as or higher than long, sparingly dentate*; the parenchyma cells all of one kind and rather thin-walled, straight and equal to about 4 wood tracheids, the upper and lower walls strongly pitted, the terminal walls straight or diagonal and apparently not pitted, the lateral walls with simple, round or lenticular pits of medium size, 2-4, chiefly 2 per tracheid. Bordered pits on the tangential walls of the summer tracheids small and not numerous, those on the radial walls rather large, round, or oval in one compact row, and generally numerous.

Tangential.—Fusiform rays rather numerous, short, the broad central tract with thin-walled parenchyma chiefly broken out; the unequal terminals composed of broad, oval cells chiefly in one row. Ordinary rays low to medium, uniseriate, not materially contracted by the interspersed tracheids; the parenchyma cells somewhat unequal and variable from oblong (in the summer wood) to broad and oval or round (in the spring wood).

* Possibly due to conditions of decay.

In the collections of 1905, under number $\frac{1007}{6d.}$, there were two impressions of cones which obviously represent a species of pine (Pl. II.). They are entirely free from associated foliage or other portions of the tree by means of which they might be more fully determined and correlated with known species. Although somewhat distorted by displacement of their matrix, their essential characters are fairly well preserved and may be described as follows:—

Cones narrowly ovate or oblong ovate; the scales upwards of 1·1 cm. broad and 3 mm. thick at the upper ends, strongly and transversely keeled and terminating in depressed, round or transversely elongated umbos without (?) prickles.

From the above description it is quite clear that the cones represent a hard pine, and upon careful comparison with the excellent figures and descriptions given by Sargent (**55**), it becomes apparent that they are most directly comparable with P. glabra among existing species.

Although the two localities for the stem and cones are not identical, they represent the same horizon, and probably the same deposits, so that in view of the essential relationship established above, it is probably justifiable to consider that both cones and wood represent the same species. This view is strengthened by the fact that independent determinations brought the two to substantially the the same species.

$\frac{250}{\text{a, b, c, d, f, h, i, k, l, m, of 1905.}}$ CUPRESSOXYLON MACROCARPOIDES, Penh.

In 1904 I described a new wood, found among the undescribed specimens in the Peter Redpath Museum, under the name of Cupressoxylon macrocarpoides (**47**), because of its striking resemblance to the existing Cupressus macrocarpa, with which it is possible it should be fully identified under the same name, but of which it is to be regarded as the ancestral form in any event. These woods were all recorded as from the Cretaceous formation near Medicine Hat, Alberta, the precise locality being Twenty-Mile creek.

In the 1905 collection from the Kettle river, large numbers of specimens representative of this tree were again met with, and in the main, they are much better preserved. That this genus has already been recognized as an element of both the Cretaceous and Tertiary floras, has been shown on former occasions, and especially by the occurrence of C. dawsoni, Penh., in the Eocene of the Great Valley and Porcupine Creek groups, as well as in the Cretaceous of the South Saskatchewan, near Medicine Hat (**47**). This extended geological range is quite in harmony with the idea that the genus as a whole is an old one, and that the present species is ancestral to, if not in all respects identical with the existing C. macrocarpa.

$\frac{250}{E}$. Ulmus protoracemosa, n. sp.

Plates IV-VI.

This plant is represented by a single specimen of calcified wood, the structure of which is fairly well preserved, chiefly with respect to the transverse section. In the longitudinal sections the structure is so altered that many of the essential details cannot be determined, and the final diagnosis must be deferred until such time as more ample and more perfectly preserved material renders it possible to draw it accurately. The provisional diagnosis nevertheless shows this wood to be that of an elm. While the wood of this genus is not known in horizons earlier than the Pleistocene, in which formation both U. americana and U. racemosa are well recognized types, the present material affords the first definite knowledge of the woody structure of a genus in formations where its leaves have been known for some time. Among existing species this wood is probably most nearly comparable with U. racemosa—a species which exhibits great structural variation along lines essentially parallel with those shown in the present case. From the details of structure available, it is perhaps not unsafe to assert that the resemblance is so close as to justify regarding the fossil as the prototype of that species, and it is therefore named with reference to this fact. The diagnosis so far as obtained is as follows:—

Ulmus protoracemosa, n. sp.

Transverse.—Growth rings very variable and with no obvious distinction of spring and summer wood; in stems of rapid growth very broad and showing a gradation of vessels and wood parenchyma; in stems of slow growth very narrow and more variable. Structure rather dense in the greater portion of the ring; the wood cells medium, rather thick-walled. Vessels of the spring wood medium, not very large, radially oval or oblong and often so disposed as to be radially 2 seriate but without thyloses; forming about $\frac{1}{2}$-$\frac{1}{3}$ the thickness of the ring and abruptly replaced by small vessels and wood parenchyma forming small to medium tracts which are more or less distant and constantly diminishing in size outwardly, sometimes forming diagonal or even tangential series, the contained vessels often lying in radial series of 2-4. Medullary rays poorly defined but rather numerous and several cells wide.

Radial.—Medullary ray cells all of one kind, straight, rather thin-walled with no recognizable markings. Vessels short and broad, the radial walls with multiseriate and chiefly hexagonal, bordered pits.

Tangential.—Rays numerous, low and broad, upwards of 4 cells wide and never uniseriate. Vessels as in the radial section.

$\frac{250}{G}$ of 1905. Ulmus protoamericana, n. sp.

Plate VII.

The specimens designated as $\frac{250}{G}$ represent another species of Ulmus in a very perfect state of preservation which permits of drawing a diagnosis with completeness. Whatever doubts may attach to the preceding species with respect to its relation to existing forms, there seems to be little or no room for denying the relation of the present material to the existing American elm, of which it is undoubtedly the ancestral form. The most prominent respect in which it differs appears to be in the rather broad zone of vessels in the spring wood, and the somewhat different form presented by the distribution of the wood parenchyma in the summer wood. Both of these features are of a variable character in the white elm and quite conformable to what is found in the fossil.

That both U. americana and U. racemosa should be represented in the same formation by equivalent forms, is in no way surprising when we recall their constant association in the Pleistocene and also in existing floras. There is therefore no reason why the prototypes of these familiar species should not be similarly associated in the early Tertiary. The diagnosis of this species is as follows:—

Ulmus protoamericana, n. sp.

Transverse.—Growth rings variable, often very narrow, with no obvious distinction between spring and summer wood except through the location of the large vessels. Wood cells at first rather large and rather thin-walled, soon reduced and passing somewhat gradually into small, thick-walled cells at the outer limits of the growth ring, very variable and unequal throughout, rarely disposed in radial rows, the structure dense. Vessels at first large and prominent, often with round or oval, transversely or more generally radially 2-3 seriate: forming a zone $\frac{1}{3}$ to $\frac{1}{2}$ the thickness of the growth ring and abruptly followed by smaller vessels with wood parenchyma which form tracts of variable extent, radially or transversely extended, or more or less coalescent so as to form diagonal tracts or tangential zones of indefinite extent; the parenchyma elements within such tracts often conspicuously resinous. Medullary rays prominent, numerous, upwards of 4 cells wide, sparingly resinous.

Radial.—Ray cells all of one kind, low and more or less contracted at the ends; the upper and lower walls thin and not pitted; the terminal walls sometimes thick and strongly pitted; the lateral walls without obvious pits. Vessels of the spring wood broad and short, $1\frac{1}{2}$ to 2 times longer than broad, the radial walls with multiseriate, hexagonal pits with large, transversely oblong pores; the smaller vessels fibrous, but with similar construction, the pits often reduced to a single row; thyloses of the large vessels often strongly developed, but more or less strictly localized.

Tangential.—Rays numerous, medium, upwards of 4 cells wide; the small, rounded-hexagonal cells forming a dense structure. Vessels as in the radial section.

$\frac{250}{c}$ **of 1903.**

Ulmus columbiana, n. sp.

Plate VIII.

Among the woods represented in the collections of 1903, was a specimen believed to be a new species of Rhamnacinium, and provisionally referred to that genus under the number $\frac{250}{c}$. A more critical examination proves it to be an elm of a type not readily assignable to any known species. Its diagnosis is as follows:—

Transverse.—Growth rings rather broad and well defined. Tracheids not very thick-walled, gradually passing into a thin and poorly defined limiting zone upwards of 8 tracheids thick. Medullary rays numerous, 1-4 cells wide, resinous, distant chiefly one but sometimes three rows of vessels. Vessels oval or round, more or less in radial rows, radially 1-5 seriate or sometimes tangentially 2 seriate; the larger vessels occupying a zone of variable width in the spring wood and often preceded by a series of smaller vessels, more or less abruptly diminishing and becoming more scattering toward the summer wood where they form more or less scattering groups or finally become merged with the wood parenchyma. Wood parenchyma very variable and often apparently wanting, but when prominent surrounding groups of vessels or forming isolated and commonly tangentially disposed tracts of variable size near the outer limits of the growth ring.

Radial.—Vessels short and commonly broad, the hexagonal, multiseriate pits with transversely slit-like pores. Medullary rays numerous and medium to rather high, the cells all of one kind though often much shortened; the upper and lower walls rather thin, or in the short cells thick and much pitted; the lateral walls multiporous when contiguous to vessels. Vessels of the medullary sheath spiral and scalariform, the adjacent parenchyma filled with starch. Wood parenchyma cells about eight times longer than broad.

Tangential.—Rays of two kinds; the uniseriate rays low, inconspicuous, not numerous; the multiseriate rays numerous, resinous, lenticular, upwards of 5 cells wide, the terminals not prolonged, the cells all of one kind and chiefly thin-walled.

$\frac{1007}{1,\ 2a}$ of 1905. EXOGENOUS WOOD. UNDETERMINABLE.

This number represents two fragments of wood a few centimetres square. One is a separate fragment, carbonized throughout and evidently a piece of exogenous wood. The other fragment, still adherent to the original matrix, is about 2-3 mm. thick, fully carbonized, and showing both growth rings and medullary rays. The material is too friable and too fully carbonized to make sections possible.

$\frac{1007}{2b,\ 5}$ of 1905. PHRAGMITES, sp.

Two fragmentary specimens of very imperfect leaves which cannot be referred to anything more definite than Phragmites.

$\frac{1007}{3c}$ of 1905. POTAMOGETON, sp.

Among the small fragments embedded in the general matrix of specimens from locality 1007, there were noticed several small, oval bodies, evidently of a composite character and very suggestive of the fruit of a Carex or one of the Naiadaceæ. Upon critical examination the conclusion was reached that they belonged to the latter family, of which Potamogeton was found to be the genus presenting the most favourable basis for comparison. From that point of view they were found to compare closely with such species as P. mysticus, P. confervoides, P. obtusifolius, P. vaseyi, or P. diversifolius, being most directly related in point of size, form and variations with P. obtusifolius. The entire absence of foliage makes it impossible to correlate it any more definitely with existing species, and it is therefore unwise at present to assign any specific name.

A review of the American history of this genus shows that on the whole, it has heretofore been recognized chiefly with respect to the Pleistocene formation, in which Penhallow (**48**, **49**), and Dawson (**6**,**75**) have recorded a number of species represented by their foliage. Knowlton (**25**) has similarly recorded the genus as occurring in the glacial deposits of West Virginia, but in all of these cases the plants found may be directly correlated with existing species. Lesquereux (**42**, 142, pl. xxiii., f. 5—6) has recorded the existence of Potamogeton in the Green River group at Florissant, Colorado, where two species are recognized: the one, P. verticillatus, Lesq., being known by its leaves only; the other, P. geniculatus, Al. Br., being known through both fruit and leaves. There is, therefore, no substantial reason for questioning the character of the fruits as described in the present instance.

$\frac{1001}{3}$ of 1905. ULMUS, sp.

An undeterminable species of elm, represented by a fragment of a leaf, showing nothing but venation, and probably referable to one of the woods of the same genus described.

$\frac{1001}{2}$ of 1905. BETULA, sp.

This specimen embraces three fruit bodies, two of which are but imperfectly represented, while the third shows a perfect, oval form, 4 x 8 mm., with well defined scales. It is a small cone, representing the fruit of Betula, possibly the same as $\frac{250}{1c}$. On the same slab are various fragments of stems, more or less carbonized. These are several centimetres long and upwards of more than a centimetre in width. Their character cannot be determined, but they apparently represent small branches of some woody exogen, possibly of Betula itself.

$\frac{1001}{1}$ of 1905. TAXODIUM DISTICHUM.

The only representative of this genus is to be found in a portion of the male inflorescence, about 4·7 cm. long. The central axis is rather stout and it bears several well-defined inflorescences, together with one or two which are detached. These latter show the characteristic features of the male flowers of Taxodium, as already recognized by Knowlton (**34**), in specimens derived from the Mascall Beds of the John Day Basin (U. Miocene) of Oregon.

CRETACEOUS.

LEAVES OF ENDOGENS.

The only specimen under number 1433 showed on one side, two small fragments of leaves which, from their obviously parallel venation, are to be regarded as belonging to some endogenous plant, the nature of which could not be determined.

PINUS, sp.

On the opposite side of 1433 is a single leaf of a pine. The same leaves again appear in specimen $\frac{1428}{5}$. In $\frac{1428}{3}$ there is a seed (Fig. 1) which appears

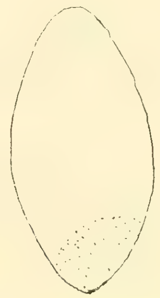

FIG. 1. Pinus sp. A seed, probably of a pine. × 4.

to be that of a pine, though the impression is not a very good one, and it may belong to the same species as the leaves just referred to.

$\frac{1428}{1}$. GLEICHENIA GILBERT-THOMPSONI, Font.

Plate IX.

Among the collections of 1905 there were a large number of fragments of various sizes, from locality 1428, representing the bipinnate frond of a fern. In a few instances these were so large and complete as to permit of a ready recognition of all the essential characteristics. The description obtained from these latter is as follows:—

Frond twice pinnate; the rachis upwards of 7 mm. broad; pinnæ 1·3 cm. distant and widely spreading at angles of 76°-90°, the latter apparently the result of displacement, upwards of more than 10 cm. in length; the rachis 0·5 mm. broad and very slender, linear, 11 mm. broad at the base and above the middle gradually tapering toward the apex which is not shown; in the longest, 6 mm. broad at a distance of 10 cm. from the base. Pinnules crowded but not strictly contiguous, distinct, attached by the full width of the broad base; not decurrent; 5 mm. long and 2·5 mm. wide; oblong, abruptly rounded at the broad apex or more rarely triangular and obtuse as the result of drying before burial; at first horizontal or at an angle of 89°, gradually ascending and toward the apex becoming 65°; terminal pinnules not represented in any of the specimens; venation simple with free and submarginal terminations; sori not represented.

This plant belongs to the genus Pecopteris, which Brongniart established in 1828. To it he assigned a large number of related species ranging from the

Carboniferous to the Permian, while more recently it has come to include species from the Mesozoic and even from the early Tertiary. It is therefore found that through a well defined series of related specific types, the genus, which is recognized as a very old one, is directly connected with existing types to be found in the Gleicheniaceæ, and particularly in the genus Gleichenia, as already shown by Potonié, who nevertheless retains Brongniart's original name (**54**, **53**). The former practice of adopting one name for fossils and another for recent forms when the two are recognized to have generic identity does not rest upon a sound basis, nor is it conducive to that nomenclatural simplification which is a great desideratum at the present time. It rather tends to perpetuate and emphasize the ancient idea of the radical difference between extinct and existing types, instead of directing attention toward a progressive development of related forms. There is, therefore, no real reason why the genus Pecopteris should not be known in the future as Gleichenia, to which the various species in reality belong, and our future practice will conform to this view, in accordance with that already instituted by Heer in 1875, (**35**: III., p. 44, pl. iv., v., vi., vii.), who relegates to that genus all species of the type represented by the present specimen.

In endeavoring to institute comparison with other specimens from nearly related horizons, it appears that no representative of this plant is to be found in the collections of the Peter Redpath Museum, where the most recent horizon in which any Pecopteris appears is the Upper Cretaceous. A specimen to which no specific name has been assigned, was collected by Dr. G. M. Dawson, from the Upper Cretaceous of Baynes Sound, B.C. This may possibly be the same as a species which Sir William Dawson recognized (**8**) in the material collected by Mr. James Richardson, from Hornby Island, B.C., in 1872, and which he regarded as closely approaching P. phillipsi of the English Oolite, but to which he gave no name on account of the absence of venation.

Dawson (**5**) has shown that Pecopteris browniana, Dunker, occurs in the Kootanie Series, and, as originally noted by Newberry (**44**), it also occurs at Great Falls, Montana; but since this species has now been definitely transferred to the genus Cyathites, it is excluded from further consideration. Of the thirteen species of Pecopteris enumerated by Knowlton (**37**), all except one may be readily excluded from the present case by reason of their marked differences in the character of the foliage.

Upon comparison with the European forms recorded by Brongniart (**4**), a very striking resemblance is observed to exist between our present specimens and P. arborescens. This latter is characterized by having 'Pinnæ, 7 cm. long and 6 mm. broad at the base, at first linear but then gradually and uniformly tapering toward the apex from above the middle; pinnules, 3 mm. x 1·5 mm.' While a careful comparison of the two specimens shows a remarkable resemblance, it is to be noted that the one now under special consideration is much the larger, a feature which constitutes the chief and most essential difference. Furthermore, P. arborescens is a Carboniferous type from St. Etienne, and I am not aware that it has been definitely observed in any later formation.

While, therefore, it is not altogether possible to establish specific identity between the two, there is little reason to doubt that G. gilbert-thompsoni is the modern representative of P. arborescens.

Directing comparisons to Tertiary forms, it is found that the genus is but sparingly represented in that age. Pecopteris torellii of Heer, is an element of the Eocene flora of Unga island (**42**), while it is also common to the Miocene of the island of Saghalien (**21**), but as this plant can no longer be regarded as one of the Gleicheniaceæ, but rather, as Lesquereux points out, a true Osmunda, it must be excluded from further discussion in this connection.

Perhaps the nearest representative of this type is to be found in Gleichenia zippei, Heer, from the Kome beds of Greenland (**35**: p. 44, pl. iv., v., vi., vii.). While there is a general resemblance which unquestionably brings the two into generic relation, there are important differences in the length and shape of the pinnules which definitely establish a specific difference.

We are thus brought to a comparison with the geologically most recent of all known species—P. sepulta, Newb. This plant was described by Newberry in 1882 (**45**) as having been obtained from the Eocene of Green river, Wyoming. No figure is given, but the description shows the pinnules to be confluent, united by one-third of their length, slightly curved upward and flabellate on the upper side.

It is thus clear that P. sepulta is not even remotely related to the one under discussion, and from the evidence collected, the latter must be regarded as altogether a new one, for which a definite name is demanded. But since the above was written, a copy of Ward's latest contribution to our knowledge of the Mesozoic flora has come to hand (**57**:616), and in this way my attention was at once drawn to a description and figures of Gleichenia gilbert-thompsoni, as originally described by Fontaine, as being at least closely similar to the Skagit river specimen. Unfortunately, Ward gives no detailed description of this specimen, a fault which equally applies to most of the other specimens dealt with, and one is obliged to rely wholly upon the figure which, fortunately, is most excellent and apparently of normal scale. Careful measurements of the figure give the following diagnosis:—

Frond twice pinnate: pinnæ 1—1·2 cm. distant and inserted at angles of 55°—60°, more than 6·5 cm. long and linear within that limit, 11 mm. broad. Pinnules crowded, more or less contiguous but wholly distinct, attached by the full width of the broad base; not decurrent; 6 mm. long and 3.5 mm. wide; oblong-linear and abruptly rounded at the broad apex; inserted at angles ranging from 67°—90°, with intermediate variations resulting from displacement; only the central midrib shown.

A comparison of this diagnosis with that for the Pasayten river specimen will at once show that the only essential difference between the two lies in the size of the pinnules— a difference which may well belong to different parts of the same frond. It is thus possible to conclude that our specimen is identical with Fontaine's species.

In the collection of 1905, number $\frac{1428}{2}$ comprises a number of linear fragments devoid of structure or surface markings, though sometimes giving evidence of the presence of vascular bundles in the interior, and rarely showing a somewhat carbonized surface. They are always associated with fronds of Gleichenia gilbert-thompsoni, and there is every reason for regarding them as fragments of the stipes of that species. It is also found upon comparison, that they are identical with similar fragments contained in the collections of 1903 and designated as $\frac{471}{1-13}$. In the preliminary report upon that material, these specimens were referred to as 'representing portions from the rachis of a fern,' but owing to lack of sufficient evidence, regarded as 'essentially of no value for stratigraphical purposes.' Close comparison with the remains of C. gilbert-thompsoni, not only confirms this conclusion, but enables us to draw the further inference that they are probably parts of the same plant.

Specimens 1436 of the 1905 collections, show a single instance of short fragments which are also to be referred in a similar way to some fern of which they are parts of the rachis, and the conclusion is justified that they are identical with 471 of 1903, and $\frac{1428}{2}$ of the 1905 collections.

$\frac{1430}{2}$ GLEICHENIA, sp.

A single specimen, under number 1430, shows a fragment of a bipinnate fern frond, which is unquestionably a Gleichenia, conforming to the following description:—

Pinnæ alternate, 5 mm. broad, linear and distant 5 mm. and approximate or slightly overlapping, more than 4·5 cm. long, the apex unknown, uniformly inserted upon the rachis at an angle of 82°; pinnules alternate, ovate, unequal and crowded with the margins somewhat overlapping, the apex round-obtuse, the broad base distinctly rounded, the midrib usually at an angle of 55° with the rachis of the pinna.

The very imperfectly preserved form of this specimen, and the fact that only one fragment is available, makes the present determination open to some question, and under these circumstances it does not seem expedient to supply a specific name. So far as it is possible to reach a final conclusion, this plant appears to approximate closely to the European Pecopteris sulziana of Brongniart (**4**: pl. 105, f. 4), which differs from it in the shorter and more rounded pinnules attached throughout the full extent of the very broad base, their equal form and an angle of 75°. They resemble one another with respect to the intervals between the pinnæ (5 mm.) and in the proximate, slightly overlapping pinnules. It is therefore possible that P. sulziana is the ancestral form of the one now under consideration.

$\frac{1430}{12}$.

CLADOPHLEBIS SKAGITENSIS, n. sp.

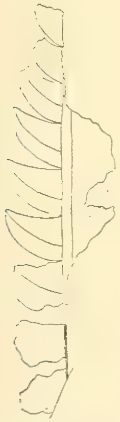

FIG. 2. Cladophlebis skagitensis, n. sp. × 1/1.

This species is represented by several fragments of fronds, the largest of which is 5·5 cm. long and 15 cm. broad in its complete state, but none of the fragments are altogether satisfactory for purposes of description. The following description has been obtained:—

Pinnules distinct, somewhat falcate, 6 mm. broad at the base and 7 mm. long, inserted on a rachis 1·5 mm. broad, the apex acute.

During the past year I have had occasion to recognize several species of Cladophlebis from the Kootanie of the Crowsnest Coal Fields at Michel Station, and from the Lower Cretaceous of the Nordenskiöld river, but the present specimen is not comparable with any of them (**1**). In 1893 Sir William Dawson recorded a fern from the Upper Cretaceous of Vancouver island, under the name of Cladophlebis columbiana, but there is no ground for comparison here, for the reason that the plant so named can hardly be regarded as a Cladophlebis at all, and upon this point Sir William Dawson himself expressed doubt (**12**). A very close resemblance is to be noted between this plant and Fontaine's C. virginiensis (**19**). The chief, and perhaps the only difference, is the one of size, and it may be that they should be regarded as identical, but for the present it seems better to adopt a provisional name for the British Columbia specimen, which is, therefore, called C. skagitensis.

$\frac{1430}{7,\ 8}$.

ASPIDIUM FREDERICKSBURGENSE, Font.

Number $\frac{1430}{7,\ 8}$ embraces numerous fragments of a bi-pinnate frond, showing only a portion of the termination of the pinna in each case. The form of the pinnules varies somewhat greatly and presents numerous gradations between the two extremes precisly as in Fontaine's Aspidium fredericksburgense, which this plant undoubtedly is. This species, originally described by Fontaine from the Potomac Formation at Fredericksburg, Virginia (**19**), has since then been recognized by Dawson (**5**) in the early Cretaceous at Anthracite, B.C. It will be readily recognized that so strongly defined a Lower Cretaceous type as this is, must have special value in determining the horizon in which it may be found.

$\frac{1430}{3}$. NILSONIA PASAYTENSIS, n. sp.

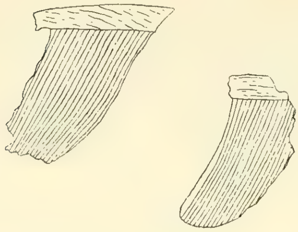

FIG. 3. Nilsonia pasaytensis, n. sp. × 1/1.

Number $\frac{1430}{3}$ embraces two small specimens, each of which represents a single pinnule of a compound leaf, attached to a strong rachis. Each pinnule is approximately triangular in outline, with a broad base and a somewhat narrow though obtuse apex. The margin is entire and the whole organ is transversed by prominent and parallel nerves about 1.5-2 per mm., which extend from the base to the apex. This species is quite distinct from anything hitherto described from Canadian localities, although Dawson (**9**) published a new species from the Upper Cretaceous of Baynes Sound, Vancouver island, but from the published figures which show a larger plant with a very different form of pinnule, there would seem to be no connection between the two.

In Ward's most recent contribution to the Mesozoic flora of North America, he publishes a description and figures of a species of Nilsonia from Thompson creek, Douglas County, Oregon. This he identifies with N. nipponensis, which Yokoyama had previously described from Japan, and which Ward thinks may be also comparable with various Jurassic species from Siberia, which Heer has described under the names of Peterophyllum and Anomozamites (**57**: p. 94, pl. xvii, f. 8-10). On comparing our specimen with those figured by Ward, a very striking resemblance is to be noted with respect to individual pinnules, but it is to be observed that within the limits of the same leaf, the pinnules show a somewhat wide variation of such a nature that taken individually, several species might be made from the parts of one leaf. It is, therefore, quite possible that our specimens are really representative of N. nipponensis, but as such a conclusion is not wholly justified by the nature of the material now in hand, it is thought that a separate name to be employed tentatively, would be altogether more appropriate, and it has, therefore, been named with respect to the locality from which it was derived.

$\frac{1430}{1}$. CYCADITES UNJIGA, Dn.

Under number $\frac{1430}{1}$ are included several fragments of pinnate leaves with strong and rigid, linear and conspicuously nerved pinnæ given off from the main rachis at angles of 65° to 70°. The angles thus indicated deviate somewhat from those given by Dawson (9) in his description of Cycadites unjiga, but in this species, as in C. confertus, Murr., from the Jurassic of India, it is obvious that the angles of the pinnæ cannot be relied upon for diagnostic purposes, because of the positions assumed as the result of displacement. A careful comparison with the original text shows that if the angles are to be relied upon, the descriptive text is to be taken as erroneous and should be recast. Both Dawson's specimens and those now under consideration, are closely comparable with C. pungens, Lesq. (43), from the Dakota Group, and it is altogether probable that future comparisons upon the basis of more complete material, will show them to be identical.

In the 1903 collections, several specimens represented by the numbers $\frac{471}{14b,\ 15a,\ 16}$ show pyritized fragments of leaves occasionally with a strong midrib, were originally determined as representing the pinnæ of a Cycad. This they no doubt are, and it may now be assumed that they represent the same species as $\frac{1430}{1}$ of the 1905 collections.

$\frac{1428}{6}$. Glyptostrobus europæus ? (Brongn.), Heer.

One specimen only, showing a small fragment of a leafy branch.

$\frac{1428}{4}$. Salix perplexa, Knowl. (?).

A single specimen representing the lower three-fourths of a leaf, appears to be identical with Knowlton's Salix perplexa (34). The chief difficulty in this comparison is to be found in the fact that this species was derived from the Mascall Beds of the John Day Basin at Van Horne's Ranch, and it is therefore of Miocene age, being known in no other horizon. This reference must therefore be taken with reservation.

$\frac{1430}{5}$. Populus cyclophylla, Heer.

One leaf only, represented by a very imperfect and badly crumpled fragment, which makes definite identification very difficult. If correctly determined, the present specimen finds its representative in the Dakota Group of Nebraska, etc., (46).

$\frac{1430}{11}$. MYRICA SERRATA, n. sp.

FIG. 4. Myrica serrata, n. sp. × 1/1.

This genus is represented by two fragments of leaves of the generalized type presented by M. torreyi, Lesq. (**56**: pl. xl., f. 4), but much smaller, more sharply and regularly dentate, and thus more nearly approaching M. scottii of Lesquereux, as figured by Knowlton, from the Laramie of the Yellowstone National Park (**34**: pl. lxxxiv, f. 6), though it can hardly be said to conform as well to Lesquereux' original description and figure based upon specimens from the Green River Group at Florissant, Colorado (**12**: p. 147, pl. xxxii, f. 17-18). It has thus been considered desirable to designate it by a distinctive name.

$\frac{1430}{6}$. QUERCUS FLEXUOSA, Newb. (?).

Several poorly preserved fragments of leaves, appear to be identical with Newberry's Quercus flexuosa (**46**: p. 74, xix, f. 4-6), from the Cretaceous of the Puget Sound group at Chuckanutz, Washington.

$\frac{1430}{9}$. QUERCUS CORIACEA, Newb.

This number embraces several small leaves nearly entire; fragments showing the entire margin, form and characteristic venation of Quercus coriacea; also one specimen with three nearly complete leaves *in situ.* These all agree fully with Newberry's figures and descriptions (**46**: p. 73, pl. xix, f, 1-3) of the species which are originally obtained from the Puget Sound Group at Chuckanutz, Washington.

$\frac{1430}{4, 10}$. SASSAFRAS CRETACEUM, Newb.

This species is represented by two fragments of leaves, the one showing the characteristic venation, the other showing the divergence of the principal veins at the base of the blade. This species has been described by Newberry (**46**) as a recognized element of the flora of the Dakota Group.

$\frac{471}{71\text{-}32}$. ENDOGENOUS LEAVES.

Pyritized leaves of various widths upwards of 15 mm., apparently representing some endogenous plant.

$\frac{1430}{13}$. FRUIT OF AN EXOGEN ?

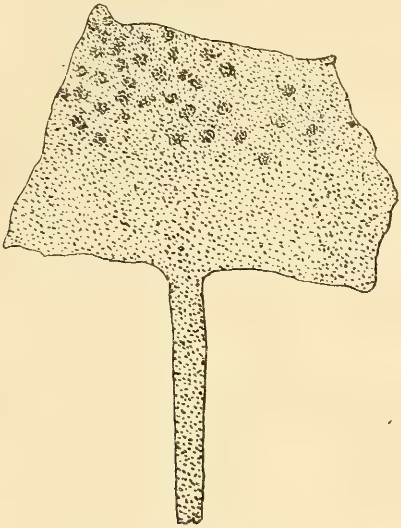

FIG. 5. Dorstenia? sp. × 4.

Number $\frac{1430}{13}$ represents a single specimen of unrecognizable character, but apparently a broad fruit which answers to the following description:—

Peduncle 1 mm. broad and 8 mm. long, bearing at its upper end a broad, four-sided disc 12 mm. at the base, 6 mm. wide at the summit and 8 mm. high, without structural markings of any kind except a finely granulated surface strongly suggestive of the presence of small seeds or akenes. While the observed form may have been derived from crushing, the entire aspect of the specimen, together with the granulated surface, strongly suggests a fruit of the type of Dorstenia.

If the suggestion thus indicated may be relied upon, it would harmonize with the very general occurrence of representatives of the Urticaceæ in Cretaceous formations, such as Ulmus, Ficus, etc. The specimen might be referred provisionally to Dorstenia.

$\frac{1428}{7}$. UNDETERMINABLE.

Several specimens under number $\frac{1428}{7}$ show fragments of dichotomously branching remains which cannot be satisfactorily correlated with any known species. They strongly suggest a variety of well-known forms, including Hymenopteris, Czekanowskia, Baieropsis, Potamogeton and Naias, with none of which a satisfactory relation can be established; and upon careful consideration and comparison, the conclusion has been reached that they represent the larger veins of exogenous leaves, possibly of the type of Platanus, which have become skeletonized and broken up, thus leaving the peculiar fragments observed. This conclusion will satisfactorily meet all requirements.

Summary and General Conclusion.

In summarizing the foregoing results it is hoped to answer more or less completely, several questions which have been raised as to the age of the deposits in which the fossils occur. The precise nature of these problems may be best understood by quoting from the original letters of transmittal and information, to the effect that 'Nos. 1428, 1430, 1433 and 1436 were collected from a large area of what has always been known as Lower Cretaceous, occurring at the Boundary (49th Parallel) Line between the Pasayten and Skagit rivers. There seems to be at least 28,000 feet of this series altogether, and it appears to correlate with the Shasta-Chico Series. I am particularly anxious to know whether 1428 is older than 1430 in its facies, and still more to know whether both are really Cretaceous.' And later, in answer to questions as to the relative positions of 1428—1436 of the 1905 collection, and 471 of the 1903 collection, the reply was that 'The locality of No. 471 is about one hundred and twenty miles east of that of 1428—1436; the former near to Rossland, the latter on the summit of the Cascade mountains. The age of the Rossland volcanics and of the ash beds or sediments in which these obscure 471 specimens occur, is not at all understood, and I was hoping for some indication as to whether these rocks are even later than Palæozoic. The two occurrences are completely separate in geological and geographical relations, but there is no good reason why both should not be Cretaceous.'

In discussing the regional distribution of the various collections, they may be divided conveniently for geological purposes, into two groups. Within the first are embraced Nos. 250, 1001, 1007, and 271. Specimens were taken from locality 250 on two separate occasions, *i.e.,* in 1902, and again in 1905. In 1905 also, collections were made from localities 1001 and 1007, both of which are on the Kettle river and near to No. 250; while locality 271 of the 1903 collection was on an affluent of the Kettle river. The proximity of these various collections enables us to consider them essentially identical, and the plants derived from them will be treated as of one flora.

In this connection it will be worth while to recall previous determinations of plants from the Red Deer river, from the Similkameen valley, from Quilchena and from Coutlee. All of these floras will have to be compared with one another and with that of the Skagit river [Pasayten river]; in consequence it should be kept in mind that, with the exception of the first, all of these localities fall within the limits of the Kamloops sheet, within which area Dr. George Dawson has shown that the Tertiary formation shows 'two well marked horizons of stratified deposits,' and with respect to the causes giving rise to them, 'it is probable that the Similkameen beds may correspond in time with one or other of these horizons, and their appearance and mode of occurrence accords best with the hypothesis that of these two they represent the lower or Coldwater horizon, but for the present this correlation stands merely as a probable conjecture.' (16: p. 75B.)

An enumeration of the various types of plants found in the localities indicated by the above numbers, gives the following:—

Taxodium distichum	Leafy branch.
Cupressoxylon macrocarpoides	Wood.
Picea columbiensis	Wood.
Cyperacites haydenii	
Cyperacites, sp	
Phragmites, sp	
Betula, sp	Fruit.
Ulmus protoracemosa	Wood.
Ulmus protoamericana	Wood.
Ulmus columbiana	Wood.
Ulmus, sp	Leaf.
Potamogeton, sp	Fruit and leaves.
Fern stipes	
Exogenous wood	
Undeterminable fragments of leaves	
Pinus columbiana	Wood.

This flora represents a remarkable preponderance of woods, several of which are entirely new, and in such cases previous knowledge cannot be utilized as an indication of the horizon they represent. There are, nevertheless, certain well defined forms of known value, and these will serve as a means of determining the horizon in connection with the general facies of the entire flora. From the list, we may nevertheless exclude the fern stipes, the exogenous wood and the undeterminable leaves as throwing no light whatever upon the problems before us.

The genus Picea, although somewhat sparingly known in the fossil state, is, nevertheless, found to be distributed through a rather wide range of horizons. It is a well recognized and rather abundant element of the Pleistocene flora, in which several existing species are represented by both wood and leaves (48), Similarly also, Knowlton (38: p. 215) has shown that existing species are still undergoing deposition wherever local glaciation is in progress. Picea quilchenensis, Penh., has been recognized somewhat recently in the Oligocene of the Quilchena basin, British Columbia (1), but as the plant is represented solely by its leaves, it is impossible to determine its precise relation to other fossil forms, although the character of the foliage offers a suggestion that it may be related to the existing P. breweriana or P. sitchensis. More recently, Berry (3) has determined the extension of the genus into the Upper Cretaceous formation of New Jersey. In the Cliffwood clays he has found beautifully preserved cones which he regards as representing a species comparable with the existing P. excelsa.

In 1904 Knowlton recorded the occurrence of a Picea in the Upper Eocene deposits at Kukak bay, Alaska, (**33**). This plant, which he designates as P. harrimani, is represented by its cones only, but these are in a fine state of preservation and permit of the inference that it most nearly resembles P. sitchensis among existing species.

The present evidence shows our knowledge of Picea in the fossil state to be based upon the wood chiefly, though to some extent upon the cones as representing three species within the limits of the United States and Alaska, but as these latter are in no way related species, they furnish no very precise basis for conclusions respecting the geological age of the horizon from which P. columbiensis has been derived. While our present limited knowledge of the genus leads us to believe that it should be looked for in the early Cretaceous at least, its present aspect is definitely Tertiary and chiefly Eocene.

Cupressoxylon was first recognized by Penhallow (**47**) in the Cretaceous formation of Medicine Hat, where the wood was found in abundance. Its more recent appearance in the deposits of the Kettle river, where it is also found in the form of wood, gives somewhat conclusive evidence of the wider range of distribution of some of our existing species. This is wholly in accord with the general geological history of the genus, since it is found that under whatever specific name it may be recorded, it ranges from the Lower Cretaceous to the Eocene, a distribution which is not essentially affected by the fact that at least some of the species now assigned to the provisional genus Cupressinoxylon, may more properly belong to Sequoia. At the same time, since C. macrocarpoides occurs in a well recognized Cretaceous deposit, as well as in those of the Kettle river, it is clear that it cannot be held to be representative in any exclusive sense, of any particular age, and all we can say of it at the present time is, that it ranges from the Upper Cretaceous upward.

The genus Taxodium is a very cosmopolitan one, having a very wide range in geological time. Indeed, it may be said to exhibit an almost unbroken continuity of occurrence from the Kootanie and Potomac formations, through the Cretaceous to the Miocene Tertiary, and even to more recent deposits, where it connects directly with the existing species of Bald Cypress. The history of Taxodium distichum miocenum as originally defined by Heer, but as now commonly designated by the name Taxodium distichum, affords simply an instructive illustration of the relation of special types to particular horizons, a relation made all the more instructive because of the generally associated Taxodium occidentale and Glyptostrobus europæus. T. occidentale is a species of much more restricted distribution, but it is a well defined Tertiary type.

Lesquereux (**42**: p. 223), Newberry (**46**: p. 22), and Dawson (**10**: p. 79), have all shown Taxodium distichum to be a constituent of both the Miocene and Eocene Floras; while the more recent determinations of Penhallow (**1**: pp. 7 and 8) have proved it to be a component of the Oligocene at Quilchena and Coutlee, British Columbia, and those of Knowlton (**34**: p. 27), that it is a feature of the Upper Miocene of the John Day Basin, Oregon. It is nevertheless true, as shown by Penhallow, that this species is also a well recognized feature of the Paskapoo series of the Red Deer river (**1**: pp. 9 and **51**, p. 51), as well as of the Lignite Tertiary of the Porcupine Creek and Great Valley group in the western portions of Canada (**52**: p. 36). Recognizing the force of the generalization of Sir William Dawson (**14**: iv., 73) to the effect that the Miocene of Greenland, Spitzbergen and Alaska, as formerly regarded by Heer, is in reality identical with the Fort Union of the United States, a view more recently stated and adopted by Knowlton (**38**: p. 240) and now universally admitted, it now becomes possible to recognize the fact that the numerous instances of the occurrence of this tree in Spitzbergen (**22**: p. 57), Grinnell Land (**24**: p. 23), Siberia (**25**: p. 33), Saghalien (**13**: p. 22), Alaska (**39**: p. 378 and **51**: p. 214), as well as in Greenland itself (**23**: p. 60; **26**: p. 9; **28**: p. 463, and **29**: p. 89), give unquestionable proof of its wide spread and abundant occurrence throughout the Eocene of America as well as of Europe. While, therefore, it is a form essentially typical of both the Eocene and Miocene, its greater abundance in the former implies a vigor of development which it appears to have lost in more recent times, although this does not of necessity permit us to conclude that its presence in a given horizon is more indicative of the one age than the other, a relation which must be finally established by collateral evidence.

Pinus columbiana does not, in itself, afford decisive evidence as to the nature of the horizon from which it comes, but a review of the distribution of the genus Pinus as now known may serve to suggest a reasonable conclusion.

The genus Pinus, as given by Knowlton (**37**), embraces nineteen species, most of which are defined specifically, ranging from the Dakota group through the Cretaceous and Tertiary to the Pleistocene, where they become identified with existing species. But to these we may add six species of Pityoxylon, some of which are of Upper Cretaceous age, but most of which are Tertiary forms most largely represented in the Eocene. More recently, Knowlton (**35**) has also recognized the occurrence of the wood of Pityoxylon aldersoni and P. amethystinum in the Upper Miocene of the Yellowstone National Park, while on the other hand a recent publication by Ward has brought to light Pinus leei, Font. (**57**: p. 570), from the older Potomac Formation of Virginia, a case which parallels that recorded by Heer of P. crameri, Heer, from the Kome beds of Greenland. While some of the species of Pinus thus referred to are recognizable through their wood structure, many others are known only through their foliage, and, although these latter are designated by distinctive names, it is not altogether certain that they are specifically distinct or that they are different from species represented by other remains with which it is at present impossible to identify them. A very large number of known species are represented wholly by seeds, and this is particularly true of the numerous species which Heer describes from the Eocene of Greenland and other Polar regions (**22**: Vols. I.–VII.). Inasmuch as such seeds are representative of the fruit, they may be directly connected with the cones, which are the chief means of recognizing several species. Fontaine's Pinus leei from the Older Potomac of Virginia, as described by Ward (**57**: p. 570), is thus distinguished, but it is to be observed that such remains become far more abundant and characteristic in the Tertiary, where they are not infrequently preserved in a very perfect manner. This is eminently true of P. baileyi, Gard., and P. plutonis, Gard., as recorded by Starkie Gardner from the Palady beds of Ireland; or P. macluri, Heer, as recorded by Heer (**22**; p. vii.), from the Eocene of Greenland. The same is likewise true of several species which Knowlton records from the Laramie of the Yellowstone National Park (**35**), and of P. florissanti, Lesq., which Lesquereux described from the Green River group (**42**: p. 138). Some of these cones show decided relations to existing species, which is also true of P. columbiana, but the latter cannot be compared with any of the other fossil cones now known, and it therefore stands wholly by itself.

The general weight of evidence brought forward by the above analysis, would seem to indicate that while the genus Pinus may extend into the Cretaceous, it is essentially a Tertiary type, the chief aspects of which are Eocene, and it is to this horizon that P. columbiana probably belongs.

The genus Ulmus possesses peculiar significance in the present instance, not only because there are three well defined new species represented by their wood and one undefined species represented by a fragment of a leaf, but also because the genus as at present known, bears a definite relation to geological age. Ulmophyllum is a well recognized Cretaceous type which is chiefly found in the Potomac Formation, although it is also known to the Upper Cretaceous of Vancouver island (**5**); but Ulmites and Ulmus are confined to the Tertiary where they range from the Eocene to the Pleistocene, and become identified with existing species. An inspection of present records shows that out of nineteen Tertiary species, twelve are of Eocene age, while only seven are of Eocene and Miocene age, and that out of these latter only five are strictly Miocene. From this we may draw the inference that the genus Ulmus is essentially an Eocene type, and our four species from the Kettle river may also be interpreted in that sense.

The poorly defined species of Betula from the Kettle river afford very little, if anything, in the way of a reliable basis for age determinations. While the genus Betulites is a well defined Cretaceous one, being especially characteristic of the Dakota group, we nevertheless also find Betula beatriciana, Lesq., in the same horizon (**42**: p. 36), while B. perantiqua, Dn., occurs in the Upper Cretaceous of Baynes sound (**9**), and yet another not specifically defined is met with in the Upper Cretaceous of Vancouver island (**8**). Knowlton enumerates (**37**) not less than nineteen, while Ward (**56**) gives seven Tertiary species out of a total of fifteen. As, furthermore, eighteen out of these twenty-six species are distinctly Eocene, it may be concluded that in the absence of definite evidence to the contrary, any large representation of the genus would give to the flora, facies of a distinctly Eocene character.

Cyperacites haydenii, Lesq., which occurs in the Kettle River flora, and which was originally described from the Green River group (**42**: p. 140), serves to definitely indicate the probable age of the flora now under discussion. This conclusion is emphasized by the fact that the somewhat large number of species originally described by Heer (**26**: 46, 52), from Greenland and Spitzbergen, are all of Eocene age. Of these latter, Cyperacites paucinervis, Heer., is also found in the Eocene of Vancouver island (**13**: iv. 144). In the enumeration of the fossil flora of the Yellowstone National Park, Knowlton (**35**: p. 779) shows that of the four species known there, three are definitely referable to the Fort Union group, while only one is referred to the Miocene. Finally, Ward (**56**: p. 464) indicates similar relations when in his synopsis of the Laramie group, he enumerates four species, all of which he shows to be exclusively of Eocene age. From this summary it becomes obvious that Cyperacites is essentially and typically an Eocene genus, the chief aspect of which is Lower Eocene. The only exception to this which has come under my notice, is the case of an undescribed species recorded by Sir William Dawson in his description of specimens from the Kootanie group at Anthracite, B.C., (**5**: p. 91), but this reference is a doubtful one, as the species does not correspond with the usually accepted characters of the genus, or with those of the existing genus Cyperus, and I therefore exclude it from further consideration in this connection.

The reference to Potamogeton in the present instance is based altogether upon the fruit, but there seems little reason to question the correctness of this conclusion. Knowlton records seven species of Potamogeton (37), five of which are from the later Tertiary, but two are from the Eocene. Ward (**56**) shows that there are fifteen species of Potamogeton in the Eocene Flora, two of which are also common to the Senonian; while Heer defines no less than nine species from the Tertiary of Europe (**31**: I., p. 102; II., p. 88; III., p. 170), and five from the Eocene of Greenland (**29**: I, and **23**, VII), Spitzbergen (**27**: 10 and 22), and Siberia (**24**), from which it would appear that as we now know it, this genus is essentially distinctive of the Eocene age.

Phragmites is a form of plant remains which is nowhere clearly defined, though in a general way it may be recognized without much doubt. Precisely what it embraces with respect to either genus or species, it would be impossible to say at present, though in a general way it may be said to embrace fragments of broad leaves, more rarely fragments of stems or even of rhizomes of Monocotyledonous plants. The fragments of leaves are not always separable with certainty from other Monocotyledonous leaves with similar characteristics, while the stem fragments are clearly differentiated from Cyperacites. The rhizomes are usually sufficiently well characterized to be recognized with certainty. There is no correlation between these various forms relegated to a common genus, but when recognizable their characters are sufficiently definite to permit of using them for stratigraphical purposes. An examination of the North American distribution of the genus shows a somewhat wide range. Thus, P. cretaceus, Lesq., represented by both leaves and rhizomes, is a constituent of the flora of the Dakota group (**42**: p. 34, and **43**: p. 37). Dawson has reported the leaf of P. cordaiformis, Dn., from the Upper Cretaceous of Vancouver island (**9**: p. 26). Newberry reports fragments of leaves of an undefined species from the Cretaceous (**46**: p. 27, pl. xxii., f. 5), and Ward, in his Synopsis of the Laramie Flora enumerates four species as belonging to the Laramie proper, with two from the Senonian (**56**: pl. xxxii.) On the other hand, Lesquereux reports one species from the Tertiary (**42**: p. 141), and Knowlton (**35**: p. 779) reports P. latissima from the Fort Union group. Reference to Heer's well-known works (**29**, **26**, **24**, **23**, and **31**: p. 161) shows four species confined to the Eocene of Europe and Greenland, of which P. oeningensis, A. Br., is by far the most frequently represented. This summary shows nine Cretaceous localities against six Tertiary, and as these latter are all Eocene, it is clear that while Phragmites is common to the Upper Cretaceous and Lower Eocene, it is more typical of the former than the latter.

Reviewing the facts thus dealt with, we can only conclude that the flora of the Kettle river is certainly not Cretaceous, and that in its general facies it is Eocene rather than Miocene. This conclusion, however, necessarily raises an important question as to the particular age of floras previously determined and provisionally referred to the Miocene (**51**: iv., 68 and **52**: iv., 36, etc.), and especially with reference to a critical comparison with the Similkameen flora as already determined by Sir William Dawson (**10**: iv., 75). This author appears not to have been able to determine the age of the Similkameen beds to his own satisfaction, since, although he frequently makes comparisons with the Lower Miocene, to which his conclusions most strongly point, he nevertheless refers to some species as having distinct affinity with the Upper Laramie or Eocene, and to the Oligocene in particular, and in his concluding paragraph he says that 'It may be further affirmed that the Similkameen flora is closely allied to those described by Lesquereux as the Green River and Florissant floras, and which he regards as Oligocene or Upper Eocene. It is to be hoped that ere long the discovery of mammalian remains may throw further light on the precise age of the Tertiary lake basins of British Columbia' (**1**, c. iv., 90-91).

In order to clearly bring out the questions at issue, and establish the correlation of the various Eocene floras, I have reduced to tabular form all such floras as have been studied by me, and have shown the occurrence of the same species as determined by other observers. While, therefore, this table aims primarily to establish the relations of the Eocene floras, it will also show their contact with the Miocene and extension into the Cretaceous, including, however, only such species as are actual components of the various Eocene floras now under discussion.

The particular floras, the age of which is at present a matter of discussion, are Coal Gully at Coutlee, B.C., the Horse-Fly river at Cariboo, the Kettle river deposits at Midway, the Quilchena beds which are closely associated with those at Coutlee, and the Similkameen beds in the valley of the same name. As a basis of reference and comparison, the age of certain floras is well known or at least accepted. They are the Red Deer of the Paskapoo Series and essentially Fort Union group, the Union group of the Yellowstone National Park and elsewhere in the United States and Canada, and the Lignite Tertiary of the

Porcupine creek and Great valley, all of which are Lower Eocene. To this we may add the Eocene of the North Polar regions, the floras of which are Fort Union, as already shown. On the other hand, the Green River group furnishes a correct index of the Upper Eocene or Oligocene floras. From these fixed data it may be possible to establish the proper correlation of the unknown horizons.

	Cretaceous	Lower Tertiary.					Upper Tertiary. Oligocene.						Miocene.	
—	—	Red Deer River (Paskapoo).	Fort Union Group.	Yellowstone Eocene (Fort Union).	Lig. Tert. of Porcupine Creek, etc.	Eocene of Spitzbergen, Alaska, Greenland, etc.	Green River Group.	Similkameen Valley.	Kettle River.	Horse-Fly River.	Coutlee, B.C.	Quilchena, B.C.	—	—
Acer sp				x				x						
Acer sp. dubium										x				
Acerites negundifolium								x						
Ailanthophyllum incertum								x						
Alnites grandifolia		x						x		x		x		
Aralia notata			x	x						x			x	
Azolophyllum primævum								x						
Betula sp								x	x					5 out of 13 = Eocene.
" angustifolia													x	
" heterodonta													x	
" stevensoni										x				
Carpinus grandis						x		x				x		
Carya antiquorum	x ?	x	x									x		
Castanea castaneæfolia										x				
Carpolithes denticulata								x						
Catalpa crassifolia		x												
Ceanothus sp								x						
Cercis parvifolia		x												
Cinnamomum sp								x						14 out of 19 species = Eocene.
Clintonia oblongifolia		x												
Comptonia columbiana								x						
Cornus rhamnifolia		x												Apparently the same as Myrica cuspidata.
Corylus americana		x	x											
" macquarrii	x	x	x			x	x						x	

Cupressoxylon dawsoni					x									
" macrocarpoides	x								x					
Cyperacites sp	?			x				x	x				x	4 species given as Eocene.
" haydenii						x	x		x					
Equisetum arcticum		x												
" similkameenense								x						
Ficus sp		x		x				x			x			24 out of 54 = Eocene.
Glyptostrobus sp								x						
" europæus		x				x				x				
Gingko adiantoides						x		x						
" digitata?												x		
Juglans acuminata		x				x								
" laurifolia		x	x										x	
" leconteana	x ?	x												
" occidentalis		x												
Lastræa fischeri		x'												
Magnolia sp								x				x		
Maianthemum grandifolium		x												
Myrica cuspidata								x						36 out of 45 = Eocene.
Nelumbium pygmæum								x		x				
" saskatchuense		x												
Onoclea sensibilis	x	x												
Osmundites macrophyllus		x												
Phragmites sp	9	x		x										6 species = Eocene.
Phyllites carneosus		x												
Picea sp	x													
" columbiensis									x					
" harrimani						x								
" quilchenensis												x		
Pinus sp														15 species = Miocene; 1 = Cretaceous with very large numbers Eocene.
" columbiana		x												
" florissanti							x							
" leei	x													
" macluri						x								
" trunculus								x		x		x		
Planera longifolia							x			x		x	x	
Platanus nobilis		x	x											
Podocarpites tyrrellii		x												
Populus sp														15 species Fort Union + 7 Eocene generally.
" acerifolia		x												
" arctica		x				x								
" daphnogenoides		x	x	x				x						
" genatrix		x												
" nervosa		x												
" obtrita		x						x				x		
" polymorpha												x		
" richardsoni		x				x								

	Cretaceous.	Lower Tertiary.					Upper Tertiary.							
							Oligocene.						Miocene.	
		Red Deer River (Paskapoo).	Fort Union Group.	Yellowstone Eocene (Fort Union).	Lig. Tert. of Porcupine Creek, &c.	Eocene of Spitzbergen, Alaska, Greenland, &c.	Green River Group.	Similkameen Valley.	Kettle River.	Horse-Fly River.	Coutlee, B.C.	Quilchena, B.C.		
Populus ungeri		x												
Potamogeton sp	2	x												14 species = Eocene.
Pseudotsuga miocena					x					x				
Quercus sp		x						x						12 species = Fort Union + 29 otherwise Eocene.
" castanopsis												x		
" dollii								x						
" ellisiana		x												
Rhamnacinium porcupinianum					x									
" triseriatim					x									
Rhamnus sp												x		
" serratus												x		
Salix sp														2 species = Fort Union + 9 Eocene generally.
" kamloopsiana								x						
" laramianum		x										x		
" orbicularis														
Sapindus sp		x												
Sassafras cretaceum ?												x		
Sequoia sp								x					x	
" burgessii					x									
" couttsiæ		x	x	x		x								
" langsdorfii		x	x	x	x	x				x			x	
" nordenskioldii		x				x						x		
Sphenopteris bloemstrandi		x			x									
" guyottii		x												
Sphenozamites oblanceolatus		x												

Taxodium distichum	x	x	x	....	x	x	....	x	x	x	x	x	x	
" occidentale	....	x	x	....	....	....	....	....	....	....	....	x	x	
Thuya interrupta	....	....	....	....	....	....	....	....	....	....	....	x	....	
Trapa borealis	....	x	....	....	....	x	....	....	....	....	....	....	....	
Typha sp.	....	x	....	....	....	....	....	....	....	....	....	....	....	
Ulmites pusillus	....	....	....	....	....	....	....	x	....	....	....	....	....	
Ulmus sp.	....	....	....	....	....	....	....	....	x	....	x	....	5	19 species = Eocene, 7 out of 8 = Eocene.
" columbiensis	....	....	....	....	....	....	....	....	x	....	....	....	....	
" protoamericana	....	....	....	....	....	....	....	....	x	....	....	....	....	
" protoracemosa	....	....	....	....	....	....	....	....	x	....	....	....	....	
" speciosa	....	....	....	....	....	....	....	....	....	....	....	x	....	
Viburnum asperum	....	x	....	....	....	....	....	....	....	....	....	....	....	
" ovatum	....	x	....	....	....	....	....	....	....	....	....	....	....	
" saskatchuense	....	x	....	....	....	....	....	....	....	....	....	....	....	
Vaccinophyllum questum	....	....	....	....	....	....	x	....	....	....	....	....	....	

The Miocene age of the Similkameen beds has been adopted by Ami (**2**: iv., 220), who includes them in the Cordilleran Region, basing his opinion upon the determinations of plants by Sir William Dawson, and of insects by Scudder (**1**: p. 7). On the other hand, Dr. G. M. Dawson, in adopting the view that the Similkameen beds are Oligocene or later Eocene (**16**: pp. 75-76 B), bases his opinion upon the results obtained by Scudder, according to which sixteen out of nineteen species of Tertiary Hemiptera were from the Similkameen beds —all but one being new—and in their general facies of the Oligocene type, although the general fauna showed definite relations with the Middle Miocene; while Cope recognized the remains of Amyzon in the Similkameen beds which were, therefore, regarded by him as equivalent to the Amyzon beds of Oregon, and hence of Oligocene age. Dr. Dawson further observes that 'It is probable that the Similkameen beds may . . . represent the Coldwater horizon, but for the present this correlation stands merely as a probable conjecture' (l.c.). According to this hypothesis, the Coldwater horizon is within the Oligocene formation, and this conclusion is in exact accordance with the results of our present studies. Reference to the accompanying table will show that out of thirty species from the Similkameen beds, only ten, or 33 per cent, are Lower Eocene, thus leaving two-thirds as distinctly Upper Eocene and with Miocene affinities. From these considerations it would seem altogether probable that we must hereafter regard the Similkameen beds as Oligocene, and to the same category must no doubt be referred the various deposits at Midway on the Kettle river, where, out of seven identical species, three are distinctly allied to the Similkameen, and one to the Green River group, thus giving 57 per cent of Upper Eocene types. With respect to the plants from the Horse-Fly river at Cariboo, it should be pointed out that the number of species is small, and that they do not afford a fair opportunity for final judgment, but within the limits of twelve species four are definitely Upper Eocene, six are as definitely Lower Eocene and two are common to both horizons, while four species establish a strong contact with the Cretaceous; but as Taxodium distichum is a very cosmopolitan species of wide range, it cannot be said to have leading weight in a question of this kind, more especially as its chief aspect is Eocene. Alnites grandifolium is common to the entire Eocene, being found in the Red Deer River group as well as in the Similkameen, so that it affords no conclusive evidence as to the relative age of the beds in which it occurs. Whether Alnites and Taxodium be excluded or not, the general facies of the Horse-Fly river plants inclines much more to the Similkameen group than to the Fort Union or the Red Deer river, and our opinion is that they distinctly belong to the Oligocene.

The specimens from Coutlee, B.C., are but three in number, and they are altogether too inadequate to base an opinion upon. One species—Taxodium distichum—may indicate anything from Lower Eocene to Miocene. Ficus, represented by an undescribed species, may also indicate any horizon within the Eocene. The only genus of value in this respect is Ulmus, which suggests Upper rather than Lower Eocene, and it is thus quite possible that the Coal Gully deposits may be of Oligocene age, as suggested by Dr. Ami (**1**: p. 8).

With respect to the Quilchena flora, there are six species in the Similkameen, one in the Green River group and one in the Kettle river, and if we accept the Horse-Fly River and Coal Gully beds as Oligocene, then five more species must be added, thus making a representation of thirteen species in the Upper Eocene. Against this we have three species in the Fort Union, one in the Porcupine creek and six in the Red Deer river, making ten species of Lower Eocene type, while there is a very strong Miocene contact through Ulmus and Planera oblongifolia. From these facts the argument would seem to be that the facies are decidedly Oligocene rather than Middle or Lower Eocene.

The second group of localities embraces the numbers 1428, 1430, 1433 and 1436 of the 1905 collections, and 471 of the 1903 collections. The plants found to be represented are as follows:—

Pinus sp.
Gleichenia gilbert-thompsoni.
Gleichenia sp.
Cladophlebis skagitensis.
Aspidium fredericksburgense.
Nilsonia brevipinna.
Cycadites unjiga.
Glyptostrobus europæus.
Salix perplexa?
Populus cyclophylla.
Myrica serrata.
Quercus flexuosa.
Quercus coriacea.
Sassafras cretaceum.
Leaves of exogens.
Leaves of endogens.
Fruit of Exogen (Dorstenia?).
Undeterminable.

Of this list, if we eliminate the doubtful reference to Salix perplexa, we find only thirteen species which may be depended upon, but among these are some which afford a very definite indication of age. Inasmuch, however, as locality 471 is somewhat widely separated from the others, and as a special question arises in connection with 1428, it will be necessary to deal with three sub-groups, *i.e.*, 471, 1428 and localities 1430, 1433, 1436. A consideration of previously described floras which may bear some relation to the present, is also essential. They are represented by the Crowsnest Coal basin at Michel station, B.C., the Nordenskiöld river in the Yukon territory; the Vancouver and Queen Charlotte islands. Reducing the various floras which may be so compared, to a tabular form, it will be found that the specimens with which we are at present most directly concerned, establish contact with other floras at only nine points, and with respect to only six special groups. None of them can be directly correlated with the Cretaceous at Michel station, the Nordenskiöld river, Vancouver or the Queen Charlotte islands. This arises from the fact that in all of these floras the species presented are to a very large extent new, so that there is no overlapping, and they are in the majority of cases extensions of the previously known floras. This is pre-eminently true of Vancouver island.

—	471	1428	1430 1433 1436	Potomac of Va.	Amboy Clays.	Shasta.	Dakota.	Senonian.	Puget Sound.
Aspidium fredericksburgense			x	x					
Cladophlebis skagitensis			x						
Cycadites unjiga			x					x	
Dorstenia sp.—?			x						
Gleichenia sp.—			x						
" gilbert-thompsoni	x	x	x			x			
Glyptostrobus sp.—		x							
Myrica serrata			x						
Nilsonia pasaytensis			x						
Pinus sp.—		x	x		x				
Populus cyclophylla			x				x		
Quercus coriacea			x						x
" flexuosa			x						x
Salix sp.—		x							
Sassafras cretaceum			x	x			x		

Myrica serrata has no precise equivalent in any of the groups with which comparison has been made. The general distribution of the genus has been fairly well represented in the list given by Knowlton (**37**), which shows that out of the fifty-three species, less than half are Cretaceous, although they range as far down as the Potomac formation. From this it is apparent that while specific forms may be definitely associated with particular horizons, the general facies of the genus as a whole is such as to indicate an Upper Cretaceous or even Tertiary contact, rather than a Lower Cretaceous.

Populus cyclophylla, Heer, and Sassafras cretaceum, Newb. (**46**: p. 98), are both well defined elements of the Dakota flora, and they thereby give a somewhat definite indication of a specific horizon, which is certainly Upper Cretaceous. Again, both Quercus flexuosa, Newb., and Q. coriacea, Newb., are known so far only in the Puget Sound group of Chuckanutz, Washington (**46**: pp. 73, 74), once more giving a definitely Upper Cretaceous horizon. Similarly also, Cycadites unjiga, Dn., from the Upper Cretaceous of the Peace river, compared by Dawson (**9**: p. 20) with C. dicksoni, Heer, from the Upper Cretaceous of Greenland, confirms the deductions to be drawn from the foregoing facts in a very striking manner, especially as Dawson has already shown the Peace River formation to be Senonian, and thus within the limits of the Chico. Cladophlebis is a very strongly pronounced Cretaceous type, which is largely found in the Potomac formation, though it is also common to the Upper Cretaceous of Vancouver island, from which locality Dawson has described C. columbiana (**12**: iv., 55), a type, however, which is quite distinct from those generally associated with the Cretaceous, and which affords no direct point of comparison with the present species.

Nilsonia pasaytensis stands by itself as a species, but reference to the general distribution of the genus shows that although it may be recognized in the Upper Cretaceous, as recorded by Dawson (**9**: iv., 24), its range is rather through the Lower Mesozoic. Thus, Ward (**57**: p. 90 *et seq.*) enumerates four Cretaceous species, of which one is from the Kootanie and three from the Shasta series, and six species of Jurassic age, a distribution in exact accord with the limits assigned by Zeiller (**59**: p. 238), who speaks of its tolerable abundance in the Rhætic, whence it passes through the Jurassic to the Lower Cretaceous. The general evidence of distribution, therefore, is toward greater abundance in the Middle Mesozoic rather than toward its close, and in this sense the present species would afford very strong evidence of a Lower Cretaceous horizon. Furthermore, in comparing this species with those previously described by Fontaine and others, there is seen to be a somewhat remarkable correspondence with N. nipponensis, Yokoyama, as figured by Ward (**57**: pl. xvii., f. 8-10), which tends to strengthen the idea that this is at least an early Cretaceous type.

Aspidium fredericksburgense, Font., is an exceedingly well characterized plant, and there can be little doubt that the same species occurs in the flora of the Pasayten river district. It was originally described by Fontaine (**19**: p. 94, pl. xi. and xii.), from the Potomac formation at Fredericksburg, Virginia, where it is said to be one of the most common ferns.

Reviewing this evidence, we observe that there are eleven species of plants from locality 1430. Of these Dorstenia (?), which is of questionable character, and Pinus, which is chiefly represented by seeds and may indicate any one of several horizons, need to be eliminated because not specifically defined. This leaves nine well-defined species, of which three are definitely Lower Cretaceous and six as definitely Upper Cretaceous. These differences, however, are fully in accord with the correlations already established by Dawson (**9**: iv., 19), and by Diller and Stanton (**17**: p. 476; and **18**: p. 435, etc.), and we may conclude that at least that portion of the flora from the Skagit river which is embraced in locality 1430, is of Shasta-Chico age, and that it shows two well defined horizons within that series.

Directing attention to locality 1428, about which a specific question was raised with respect to its age relatively to that of 1430, it is possible to give a very definite answer. This locality has furnished four specimens of plants only. Of these one species of Salix presents nothing in the nature of reliable evidence, and it shows no contact with the other localities. Pinus is represented by fragments of leaves and seeds which also appear in locality 1433, which is presumably of the same age. Glyptostrobus, bearing a certain resemblance to G. europæus, appears only in this locality, and it may or may not be comparable with G. gracillimus, Lesq., which Dawson has described from the Niobrara horizon of British Columbia (**9**: iv. 21). But it may be recalled that Dawson (**9**: iv., 25) directs attention to a species of Glyptostrobus from the Upper Cretaceous of Vancouver island, which he refers to as comparable with G. europæus in form and size, but too obscure for certain determination. Furthermore, Knowlton (**37**) enumerates nine species of Glyptostrobus, of which five are Cretaceous, chiefly from the Kootanie and Potomac series, while one of these, G.

greenlandicus, Herr, is also found in the Kome beds of Greenland (**21**: p. 76). Our present specimen, therefore, is of generic value only, and its presence might support any Cretaceous horizon. Under these circumstances our knowledge of the actual age of 1428 must be based wholly upon the evidence afforded by Gleichenia gilbert-thompsoni. This plant was originally obtained from the Lower Cretaceous of the Shasta series, at Pettyjohn's Ranch, Tehama County, California, in 1882, by the one after whom it was subsequently named by Fontaine. Heretofore it has not been correlated with any particular horizon, for, as Ward observes, 'all that can be said of it is that its age might be either Lower or Upper Cretaceous' (**57**: p. 233). Nevertheless, its present occurrence in the Skagit river district definitely confirms its character as a Lower Cretaceous type, and at the same time it enables us to definitely correlate the deposits in which it was found, with those to which Aspidium fredericksburgense belongs. It may thus be confidently asserted that locality 1428 is of the Shasta series. This conclusion gains somewhat in force through the circumstances that locality 1436 shows the remains of fern stipes which have been found to be those of Gleichenia, presumably of G. gilbert-thompsoni.

Locality 471 is wholly represented by highly altered specimens which have been identified as the rachises of a fern, in all probability of Gleichenia. If this deduction, which is based upon very scanty and poorly preserved material, in which specific characters are not at all recognizable, should ultimately prove correct, we have once more a means of establishing a general correlation between the somewhat isolated Cretaceous areas of British Columbia. A tentative conclusion with respect to 471 would be that it represents an isolated Cretaceous island which, in the general elevation of the central ridge, was cut off from the lateral areas and subjected to more or less profound alteration as the character of the rock and plant remains suggests.

While writing these conclusions, a very interesting fact bearing upon the general correlation of the Cretaceous beds has been brought to my notice by Dr. A. W. G. Wilson, of McGill University, who asked me to determine a specimen of fern collected during the past summer. The specimen was a portion of a large slab, which it was impossible to transport from its original location. It was obtained from the Crowsnest Coal Basin, about thirty miles north of Michel Station, B.C., and it therefore belongs to the same deposits as previously reported upon by me. It, however, adds in most important ways to our knowledge of the very scanty flora hitherto obtained from these beds, since it proved to be a specimen of Aspidium dunkeri, Schimp., which has hitherto been known as an element of the Potomac flora, in which series it constitutes one of the best known and most widely distributed forms (**19**: p. 101). On this basis it is now possible to correlate the Crowsnest Coal Basin with the Shasta series, and the same may also be said of the deposits on the Nordenskiöld river, from which a limited flora has been obtained and studied.

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Plate I.

Plate II.

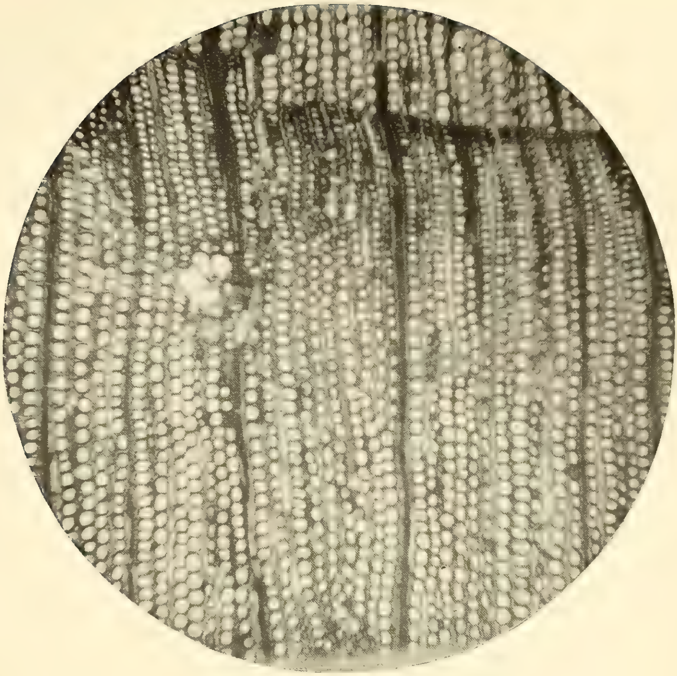


Plate III. Fig. 1.

Plate III. Fig. 2.

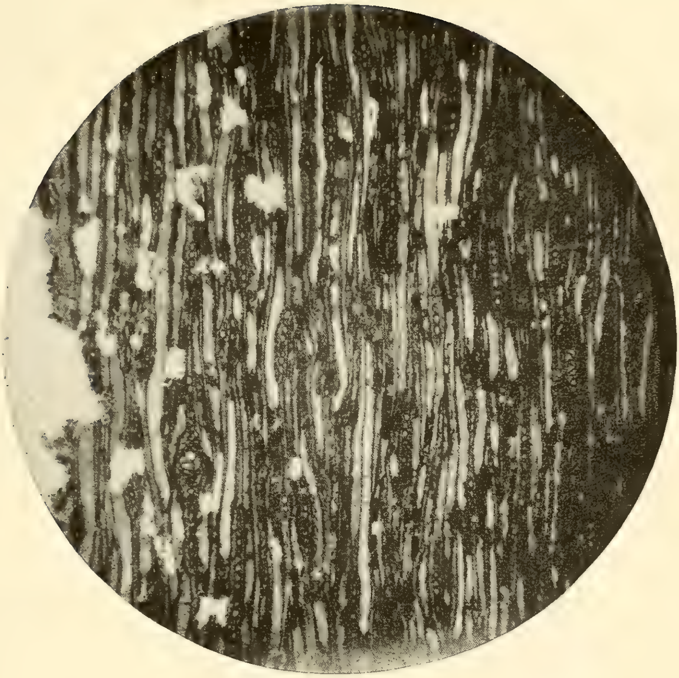


Plate IV. Fig. 1.

Plate IV. Fig. 2.

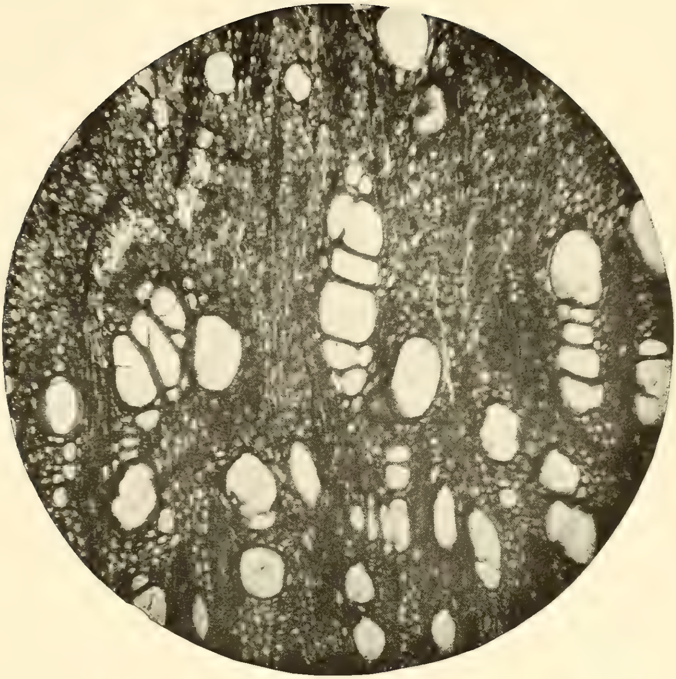


Plate V. Fig. 1.

Plate V. Fig. 2.


Plate VI. Fig. 1.

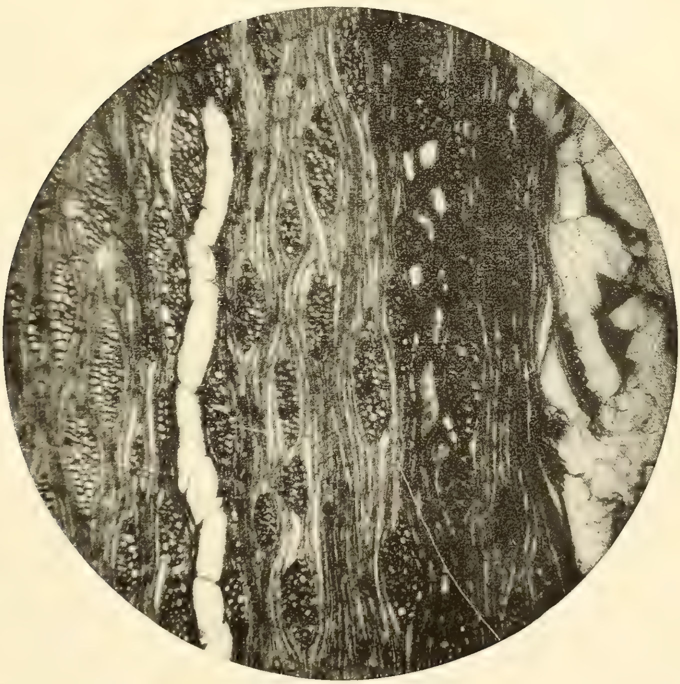


Plate VI. Fig. 2.

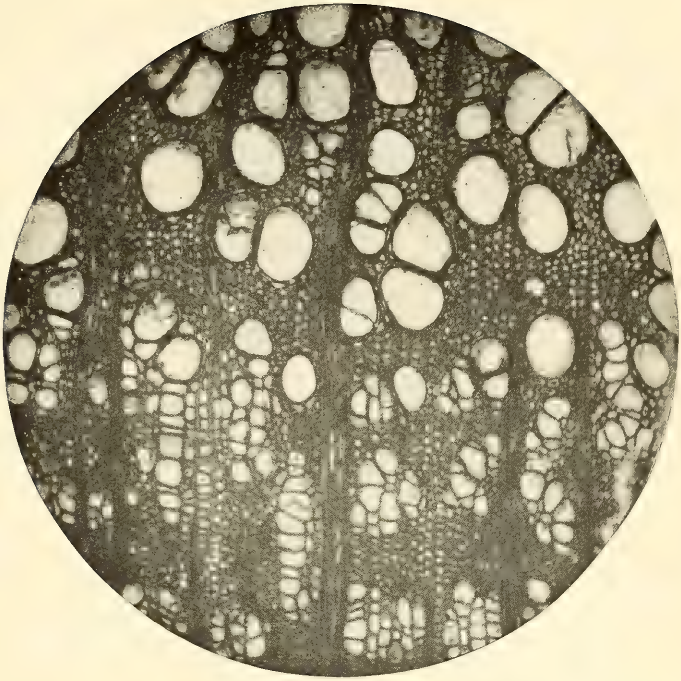


Plate VII. Fig. 1.

Plate VII. Fig. 2.

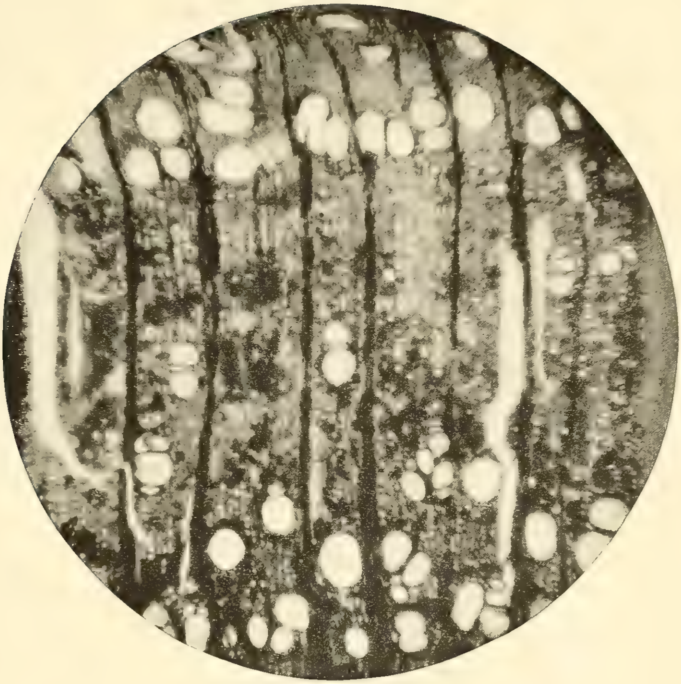
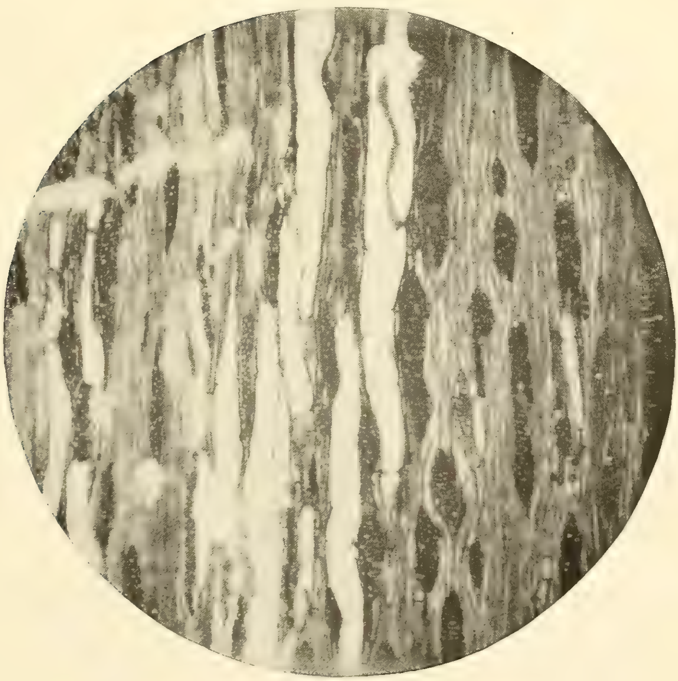


Plate VIII. Fig. 1.



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