PART I.

STRUCTURAL GEOLOGY.

By N. H. WINCHELL.

The following sketch is based on the field facts, which are given in volume iv, and on the petrographic descriptions that follow in this volume.

The Archean.

Definition of the term. As here employed the term Archean embraces that great series of crystalline and metamorphic rocks which lies below the Taconic or Lower Cambrian, and which is separated from the overlying rocks by a violent non-conformity. This horizon of separation is not known, nor presumed, to be immediately below the Olenellus horizon, as lately defined by the United States Geological survey; but it is probably considerably older than the Olenellus (or the Paradoxides*) horizon, although in strata probably conformable with strata of that horizon. These crystalline rocks, in whole or in part, have borne the names of Primary, Laurentian, Pre-Cambrian, Azoic, Eozoic and Fundamental Complex, but the term Archean, suggested by Dana, seems appropriate, and also is the most used.† As defined by him, it included Huronian and Laurentian. Owing to uncertainty as to the significance of the Canadian terms (Huronian and Laurentian) they are not employed in this discussion except for purposes of reference, although it now appears that the original Huronian embraced a part of the Taconic and a part of the Archean, while the Canadian Laurentian seems to consist largely of igneous rocks and of metamorphic clastics of different parts of the Archean. For the details the reader is referred to the plates and the special chapters accompanying them included in volume iv.

The fragmental rocks of the Archean.

Nature of these fragmentals. A large part of the fragmental debris that enters into the composition of the Archean, at least in its lower portions, is of volcanic character. It consists of fragments of minerals and of rocks that, even after more

*According to Prof. G. F. Matthew the Olenellus and the Paradoxides horizons are not always distinct, but probably blend in their stratigraphic and faunal characters. *American Geologist*, xix, 396, 1897.

†The recent restriction of the term Archean, by Van Hise and Bayley, in their monograph on the Marquette iron-bearing rocks, to the rocks supposed to be at the bottom of the "basement series" of Irving, *i. e.*, those that are without evidence of water deposition, introduces an element of confusion of which the reader should take note. It is a wide departure from Dana's definition of the term Archean.

or less alteration manifest their derivation from feldspars, from augite and from hornblende, or from an amorphous glassy substance. In the case of much of the greenstone of the Archean this debris is compacted and frequently recrystallized, giving it a striking outward resemblance to a massive rock. But it can sometimes be distinguished from a true igneous massive rock by the occurrence of clastic variations in the texture, and by the peculiar distribution of the crystals which compose it, and also sometimes by the existence of more or less globular, fine, pebble-like masses which become visible especially in the microscopic sections. In these the feldspars are distributed in a radial relation to the surrounding materials—the remnant of an original ophitic structure—while outside of these pebble-like areas the structure is that of a compact, fine, uniform clastic, though consisting essentially of the same elements. It is only rarely that augite is distinctly preserved amongst this debris, but feldspar is almost always distinctly preserved. The early augites, coming from some ferro-magnesian magma through the action of explosive ejection are apt to be converted to some form of hornblende, frequently actinolite, and this finely disseminated hornblendic mineral is the most potent cause of the prevalent green color of these rocks. The feldspars, which are more or less in fragments, usually have lost their original composition and crystalline purity, and are permeated by zoisite and calcite, and less frequently by quartz, epidote and chlorite, and at the same time are clouded by other indefinite, or kaolinic products of decay. On the other hand the feldspars are subject to another form of alteration by which their distinctness, even their outlines, are rendered almost imperceptible. This occurs in some of the later portions of the Archean, and especially in the rocks of the region of Ogishke Muncie lake. The original feldspar is replaced, in whole or in part, by a granular or micro-granulitic complex of quartz, or quartz and glassy feldspar. In some cases this substitution is so fine-grained that the shape outlined by it appears to be due to a grain of devitrified glass, or of aporhyolyte. It was found that this rearrangement of the feldspars of the Archean becomes coarser textured, and in that form is quite a prevalent mode of regeneration and of metamorphism, the significance of which is important, but which will be treated under the subtopic of "Metamorphism of the Archean Fragmentals."

Nearly always any thin section of one of these fragmental volcanic rocks discloses more or less of the iron ores. This ore may be pyrite, hematite, magnetite or ilmenite, and very often, in case of original ilmenite, this mineral is altered to leucoxene, and is accompanied by sphene.* In some instances notable amounts of nearly opaque leucoxene have been seen in these greenstones.

Epidote is quite common, and seems to have been generated in circumstances where alteration was slow and deep-seated, or was aided by other causes than simple

*Frequently in the vicinity of the iron mines more or less siderite and limonite also occur.

weathering. Various chloritic minerals, usually pennine, unite with hornblende and epidote in giving the characteristic colors. Where epidote is abundant the greenness verges toward yellow. Where the chloritic element prevails, the change has probably been due to weathering, and is carried a step further than when hornblende alone gives the green color. Quartz, which is not uncommon in these green clastic rocks, is plainly of two different sources, viz.: of fragmental origin, coeval with the rock, and of secondary origin, the result of alteration of the feldspars. Never in these rocks is there any trace of olivine, so far as observed, but this mineral, which must have been at first embraced in the debris, has been lost by alteration, and its elements divided between chlorite, actinolite and the iron ores.

As to structure, these greenstones, which, being fragmental, may bear the name *greenwackes*, are not distinctly stratiform, except in rare instances. They have a close structural relation, as well as a close mineral resemblance, to the igneous greenstones, their chief distinctions being petrographic, and mainly observable in microscopic thin sections. They acquire gradually detrital characters, *i. e.*, they become siliceous, lose their green color, and if fine grained might be denominated phyllyte, and when coarser grained they become graywackes.

At the same time it is apparent that the volcanic tuffaceous accumulation sometimes was accompanied by a copious oceanic precipitation of silica, and occasionally by iron oxide, these usually occurring somewhat sporadically in large quantities, but sometimes very continuously and very widely so as to sensibly change the composition and the color of the resultant rock. This chemical oceanic precipitation is most conspicuous in the fine-grained phases of the rock, the fine green schists sometimes becoming very siliceous and firm, or very siliceous and also reddened by hematite. When, under such a variation, the chemical elements are so abundant as to almost or quite exclude all other ingredients, the resultant rock is that which has been named jaspilyte by Wadsworth.* Frequently, however, the distinctly chemical precipitates are mingled with more or less of the cotemporary volcanic and other debris, and, in rare instances, the jaspilyte is charged with coarse fragmental materials.

Conglomeratic jaspilyte. A remarkable instance of a jaspilyte containing pebbles and even boulders of granite and other rocks occurs north of Moose lake, near the section line between secs. 20 and 21, T. 64–9. The question of the date and manner of origin of the rock termed jaspilyte was held as a debatable one until the discovery of this curious combination, although, in several of the annual reports, it was claimed to be of the nature of an oceanic precipitate.† Of this locality the following details are important:

*It is a question whether the term "jaspilyte" should be continued, inasmuch as Wadsworth's idea of the origin of this rock was very different. He described jaspilyte as a rock of igneous origin—a surface eruptive of the rhyolitic type.

†Compare, specially, *Bulletin vi*, pp. 55, 103–111.

On the portage trail from Moose lake to Wood (or Wind) lake, but near Moose lake, and near the section line between secs. 20 and 21, T. 64–9, is a very interesting locality. The country, at the time visited, had recently been burnt over and the rock was bare, showing its structure. There is a series of east-northeast and west-southwest ridges crossing the country parallel to the direction of the lake and of the islands, and on the portage trail they are quite conspicuous. At the lake is schist, quite fissile, as seen on some of the islands and the points, and argillyte, often green and falling down in large slabs, probably suitable for roofing slate. Immediately north of the portage landing rises a very singular and interesting ridge, which is steep on the south side and slants with the dip, and is somewhat more gradual on the north. The dip is 80° or 85° to the south.

This ridge is made up of conglomerate, in general terms, but shows interesting combinations.

1. It contains considerable deposits of jaspilyte, normal in all essential characters, rather magnetitic than hematitic, but considerably contorted and varying to a greenish siliceous jaspilyte and to dark slate.

2. This jaspilyte embraces rocks of different kinds as pebbles, and even occasionally as boulders, and the jaspilyte banding swings round and embraces them when large. The enclosed stones are of different sorts, but red granitic rock prevails. Such red granite boulders are also the prevalent pebble throughout that portion of this great conglomerate. Greenstone pebbles, hard, siliceous, greenish pebbles, and apparently pebbles of jaspilyte that is fiery red in color, are also included in the jaspilyte, yet, in the main, it is simply a banded jasper, nearly free from pebbles. Of one red granite boulder, about ten inches in diameter, a photograph was made (plate X, vol. iv). The jaspilyte is indigenous in the formation and its layers are frequently separated by fine green sediment, and sometimes by a coarser gritty green sediment. When the interleaved green sediment is fine and greenish it is sometimes also very siliceous, making a green flint. It is necessary to infer that the origin of the jaspilyte with its irony ingredient was cotemporary with a fragmental accumulation, the two processes operating simultaneously at the same point. No known agent is capable of such double process except oceanic water from which were being precipitated both iron and silica.

3. The conglomerate in its southern portion is characterized by a red weathering granite, but it also contains greenstone and jaspilyte and a siliceous, very fine rock like flint.

4. The jaspilyte itself occurs not only as large masses, but is strung out in small, lenticular, thin sheets, throughout the southern part of this conglomerate, and it fades out sometimes across the bedding into the general conglomerate, passing through a stage of siliceous, black or greenish slate.

5. Aside from the twisted and confused condition there is nothing further worthy of note in the southern belt, which is about thirty feet across.

On the south the rock, while plainly a part of a fragmental series, is a coarse irregular green schist containing much vitreous quartz in veins, running with the schist. This is visible only at the west end of the ridge. There is also some such quartz in irregular deposits throughout this conglomerate.

6. On the north side, while the conglomerate is continued in that direction, yet it consists wholly of greenstone debris, and is so consolidated that it looks like the massive greenstone of the lower formation. In some places it is so fine-grained and apparently siliceous, that it looks like the agglomeratic greenstone, although without the characteristic agglomeratic masses. It appears massive and uniform (No. 1821). There is another belt of jaspilyte further north, thirty or forty feet wide, and another further south about thirty feet wide, making a total thickness of about 100 feet of jaspilyte in 600 feet of conglomerate.

Conglomerates and graywackes. As already stated, this volcanic material grades imperceptibly into coarser, more siliceous and more detrital rock, forming slates, graywackes and conglomerates, whose stratification is perfectly evident. These detrital rocks are also very extensive, especially in the form of conglomerate. In these beds are fragments, well rounded, of many kinds of rocks, depending on the geographic position and the stratigraphic horizon. Probably the Ogishke and the Stuntz conglomerates are the most remarkable of these coarser beds, but between the localities denoted by these names, and especially in a wide belt at Moose lake and in the environs of Snowbank and Disappointment lakes, this conglomeratic terrane is very conspicuous and extensive. The color and composition depend on the nature of the underlying rock capable of furnishing an abundant detritus. The Stuntz conglomerate, at Vermilion lake and eastward, consists almost wholly of a gray quartz-porphyry, some of the rounded masses being a foot or more in diameter, whose source was unquestionably in some dikes of such rock which cut the older rocks of the vicinity. Eastward further this conglomerate is composed largely of greenstone debris, such as is seen on some of the islands in the southwestern part of Long lake. About Moose lake, especially on the south side, it is still coarse, but is partly of volcanic ejectamenta. The Ogishke conglomerate, which at Ogishke Muncie lake lies on the older greenstones, is largely composed of basic debris, and about Kekequabic lake embraces volcanic tuffs. Toward Saganaga lake this conglomerate changes to graywackes and slates, and at its immediate superposition on the Saganaga granite it is composed of debris from that granite, making a rock which, when firmly compacted, closely resembles the granite itself, but is distinguishable from the granite by its lacking the ferro-magnesian minerals.* One of the most remarkable phases of the coarser forms of the Archean fragmentals is to be seen at Zeta lake, which lies between Kekequabic and Ogishke Muncie lakes. The shores of this lake are almost wholly composed of a conglomerate in which appear conspicuous feldspar crystals, evidently also of fragmental origin, giving the rock the aspect of a porphyry. A similar composition is presented in the hills made of this conglomerate eastward from Moose lake (No. 2170), but here, in addition to crystals of feldspar, this conglomerate contains also fragmental crystals of hornblende (No. 2171). In numerous instances it has been observed that beds plainly of detrital origin alternate with those which contain such crystals of feldspar, indicating the proximity of volcanic vents and occasional explosive extrusion, accompanied by rapid oceanic assortment and stratification.

Origin of the fragmental rocks of the Archean. If we be allowed to infer the origin of these fragmental rocks from their nature, as given above, we are reduced to two methods of origin, viz.: volcanic ejection and ordinary erosion. Several geologists have already alluded to the probable volcanic source of much of the material which makes up the Keewatin of Canada and of Minnesota. We find that the Keewatin is separable into two parts, and that the volcanic materials are most abundant in the earlier or Lower Keewatin, while in the later Keewatin not only is there much less of distinctly volcanic debris, but also more of evident erosion and sedimentation.

The oldest detrital rocks are abundantly mingled with volcanic tuff of a basic nature. Indeed the fragmental greenstones of the Keewatin are so intimately associated with the massive greenstones that they cannot always be distinguished from them, whether in the field or in the microscopic thin section. Starting from the plainly igneous rocks, the characters gradually change by the loss of one feature after another and the acquirement of slightly different features, until finally the whole petrographic nature of the rock at one end of the series is so altered that it is not warrantable to class the rocks at both ends of the series in the same category. At one end of the series the rock considered is plainly an igneous one, and at the other it is plainly a fragmental one, and it is only by the most minute and painstaking comparisons that some of the steps in the series can be assigned to this or the other end of the scale. Without stopping at this place to specify these minute differences, or to indicate which characters are distinctly igneous and which are clastic, it is intended only to call attention to the significance of such an indefinite and gradual transition.

*The rock over which the short portage passes, from Saganaga lake to Oak lake, is a part of this conglomerate, but so closely resembles the original granite of Saganaga lake that several geologists have reported it as a part of the Saganaga granite.

In the first place, it is apparent that the supply of the basic debris, whether it was derived from erosion or from volcanic vents, was abundant and long continued; and if long continued it indicates that ordinary detrital action was limited or was excluded by the abundance of the supply. If ordinary detrital action had operated on these materials for a long period of time they would have received an indelible stamp of sedimentation and of assortment, such as is seen in the strata of later Keewatin time. It is allowable, therefore, to infer that the supply was not due so much to erosion of pre-existing rocks as to volcanic activity.

Since the larger part of these fragmentals consists of basic materials, it is apparent that the early, if not the earliest, magma was a ferro-magnesian one. Such materials, whether in a massive or in a fragmental condition, are, most of all rock substances, liable to alteration, and it is plain that in this case the fragmental and the massive have approximated each other in all outward characters.

Again, it is a legitimate inference, from the absence or rarity of plain sedimentary structures in much of these early tuffs, that they fell, not in the ocean, but on land surfaces. Such land surfaces, exempt from the action of organic matter, yet were subject to powerful atmospheric disintegration, by which the massive and the fragmental rocks, consisting of the same chemical elements and approximately the same minerals, would tend to a uniformity of texture and of structure.

These rocks, whether massive or fragmental, being the oldest known in the state, have been subjected to all the vicissitudes of subsequent geologic time. They have been pressed, depressed and upheaved and sheared. They have been heated by the ascending isogeotherms and permeated by subterranean mineralizers, and subsequently have been profoundly eroded. No actual volcanic vents have been certainly discovered, but the very evident tuffaceous character of the fragmentals has been met with in several places. These dynamic changes have also tended to unify these two classes of basic rock.

The plainly detrital rocks of the Archean lie higher, but the sedimentary stamp is also on some of the greenwackes which are described above. The true detrital rocks are graywackes, argillytes, quartzytes and conglomerates, usually quite siliceous. Some of these are in the Lower Keewatin and some are in the Upper. Those in the Lower Keewatin are, as a whole, finer grained than those of the Upper, and embrace argillitic slates, siliceous schists, quartzytes, arkoses and greenwackes, the last forming a link of transition to the older, underlying igneous rocks. Those in the Upper Keewatin are often remarkably conglomeratic and are of great thickness and extent. These occur in association with some argillytes, or black slates, and they also graduate into quartzytes and to sericitic schists.

All of the true detrital rocks of the Archean show the presence of oceanic waters, and the structure which oceanic distribution always implants on detrital rocks. But the coarseness of the debris, as well as the great thickness of the deposits, which in the Upper Keewatin reaches nearly two miles, attests the violence of the waves and currents which operated to produce and to transport the materials. In some places these materials are largely from the igneous rocks of the older formations, as in the Stuntz conglomerate, and in others they were derived from former clastic rocks. In some cases these fragments are coarse and angular, denoting powerful destructive agents but feeble transporting.

Distribution of the fragmentals of the Archean. The most important belt of the fragmentals of the Archean is found in the northeastern part of the state, extending northeastward, from Vermilion lake to Saganaga lake. It belongs to the Upper Keewatin and it lies non-conformably on the Lower Keewatin. Its materials everywhere contain fragments from the underlying, older strata. It occupies, apparently, the basin of an ancient syncline whose axis, in Minnesota, is traceable from Vermilion lake to the international boundary at Saganaga lake. The arms of the original syncline consist of granite and gneiss, and the origin of the fold probably dates from the appearance of the granite concerned. The northern arm comprises the granites and gneisses of the northern part of Vermilion lake, with the associated mica schists; these extend eastward by way of Bassimenan lake and enter Canada on the northern side of Hunter's island. Throughout some portions of this arm the igneous basic rocks, earlier than the granite, rise higher than the granite, and this is particularly the case on the southern side of Hunter's island. In like manner, the southern arm of this main synclinal valley consists of the early igneous Keewatin and its associated green schists and other schists, penetrated by a great range of granite which in its southwestern extension is known in part as the Giant's range. This granite belt, with its accompanying gneiss and mica schist, seems to come from far toward the southwest, but owing to the prevalence of the drift, it cannot be traced with certainty any further west than Pokegama falls, on the Upper Mississippi. Toward the northeast this arm sinks away and it is encroached on by the gabbro on the south, while the granite itself gives place to a characteristic massive greenstone along the north. In this way the axis of the depression has been shifted toward the south, and the overlying Upper Keewatin is brought, at Saganaga lake, immediately upon the granite itself, which further southwest constitutes the most of the southern rim of the basin. In this trough lie the rocks which, typically and specially, are herein designated Upper Keewatin. The rocks of the Lower Keewatin, mainly ferro-magnesian in character, whether massive or fragmental, and the later granite form the slopes and the summits of the rim. In general this expresses not only the distribution but the structure of the Archean lying to the north of the Cabotian gabbro and the Animikie, in the northeastern part of the state. There are doubtless other minor folds, and some of these are known to exist in the region between Vermilion lake and Rainy lake, but the rest of the Archean portion of the state is so deeply buried under the drift sheet that it is impossible to indicate, even in a general way, the distribution of the Archean fragmentals. At certain points it is known that rocks of this character appear in other parts of the state. Much of the Archean in Carlton county is of this fragmental character, sometimes bearing a considerable proportion of volcanic debris. Similar rock underlies the western part of Morrison county, while the central and eastern parts of that county are underlain by metamorphic conditions of the clastics as at Little Falls and by granite. The rocks that appear along the Minnesota valley between New Ulm and Big Stone lake are also wholly crystalline, consisting of gneisses and schists, cut by granite and diabase, but no sufficient examination has been made to warrant the statement that clastic characters do not also occur. Such characters are most likely to remain in the rocks in outcrop farthest toward the southeast, the intensity of recrystallization apparently increasing toward the northwest.

Metamorphism of the fragmentals of the Archean. It is not intended at this place to enter upon the question of the dynamics and processes of metamorphism. That question is more fully treated under the head of petrographic geology, parts ii and iii, to which the reader may be referred for many details of the microscopic changes wrought in the clastic rocks by dynamic forces and by mineralizing waters. It is only necessary here to call attention to such grand structural features as the state presents, which are dependent upon, and accompany, the principal belts of metamorphic change.

The centres of intense metamorphism are the points at which igneous rocks have penetrated the strata, whether granite or gabbro. At the borders of the granitic bosses the clastics are converted to gneisses and mica schists. In general such areas are more elevated than the non-metamorphic areas, but there are important exceptions. A glance at the geological map of the state shows the positions of these granitic and gneissic areas. In general they have a northeast and southwest direction, and between these hardened belts lie non-metamorphic rocks. It appears that very early in the geological history of the state and of the northwest, a system of crustal folding was imprinted on the earliest rocks, and that this was attended by the appearance of igneous irruption at the fissure-lines which were produced at the upward flexures. The rocks that were thus flexed and broken, so far as they appear by the study which we have given to the state of Minnesota, consisted of greenstones, quartz-porphyry and their attendant clastics, of which the former may be assumed to represent the oldest rocks, and perhaps resulted in a large measure from the consolidation of the surface of the molten globe. These rocks, especially the acid fragmental, have been subjected to earth-movements and widespread metamorphism which have given rise to a great series of gneisses and of mica schists, which in some of the annual reports has been designated by Lawson's term Coutchiching. They lie nearest the axes of upward flexure, and hence also nearest the large areas of granite. The crystallization produced in the Archean strata by this profound earth-movement is not wholly due to the act of contacting on the igneous rock, for it extends sometimes for a score or more of miles from the granitic area. It must be attributed rather to the general influence of a regional and uniform rise in the temperature of the earth's crust along those belts where this effect is seen, accompanied by an intensified action of heated water and vapor. It is apparent, therefore,—and this is in accord with observation,— that the mica schist and the gneiss may have resulted at any horizon in the early fragmentals, and that such rocks cannot from their mineral composition be taken to be older than other Keewatin rocks that do not show this metamorphism. In other words, the stratigraphic value of such a term as Coutchiching is nil, when it is applied to the general chronological scheme. It can only express a greater nearness to an accidental and local centre of metamorphism or to an igneous protrusion.

It is very true that Mr. Lawson, in his definition of the term Coutchiching* described that formation as lying non-conformably below a basal conglomerate of the Keewatin, which conglomerate, he thought, represented an important time interval and break in the Archean series. In Minnesota, however, no such conglomerate has been found at the point of transition from the Keewatin to the mica schists supposed to be Coutchiching, although careful examination and search were made with the special view of finding the break. Quite recently Mr. Coleman has shown that the conglomerate to which Mr. Lawson referred is not at the bottom of the Keewatin, but contains much Keewatin detritus and probably represents, as suggested by Mr. Coleman, a break in the Keewatin itself. It is therefore comparable with the break which is well known in Minnesota, and on the evidence of which the Keewatin is divided into upper and lower.†

The occurrence of the first grand folding may or may not have brought the flexed strata to verticality. The fact that both the earlier and the later beds are now in a vertical position rather indicates that the first folding which took place with the first granitic invasion was not sufficient to produce verticality. This uniformly vertical attitude of the Archean is one of its most marked characteristics. It implies, of course, that all the thicknesses are repeated, perhaps many times, in the measurement of any extensive traverse, the original sharp upward flexures having been denuded. In the case of the Upper Keewatin these flexures have not so universally been productive of metamorphism, and indeed have not usually been attended by granitic intrusion. The strata are compacted and in some measure a disintegrating kind of metasomatic change has passed over them. So far as known, however, they are not generally converted to gneiss and mica schist. The original minerals and rock fragments are distinctly preserved. Where, however, these Upper Keewatin strata are also penetrated by granitic dikes or by large bosses of granite, as in the region of Snowbank and Disappointment lakes, they are rendered micaceous and can often

*On the geology of the Rainy Lake region. *Geol. Sur. Canada*, vol. iii, report F, pp. 5-183 (for 1887-88), 1889.

†Report of the Bureau of Mines (Ontario), vol. vii, p. 153, 1898, "On the clastic Huronian rocks of western Ontario." *American Geologist*, xxi, pp. 222-229. "Some resemblances between the Archean of Minnesota and that of Finland."

correctly be called mica schist. In this case, however, the boulders and pebbles are still distinctly preserved, becoming more apparent on the weathered surfaces. One of the most perfect examples of the effect of metamorphism and granitic intrusion on the Upper Keewatin is to be seen about Snowbank and Disappointment lakes, and extending westward toward Moose lake. These beds are here penetrated by granite about Snowbank lake and the western confines of Disappointment lake, and by gabbro along the south side of Disappointment lake. The rocks resulting from these intrusions are quite different. The granite seems to have been accompanied by a wide regional metamorphism, and the gabbro by an intense contact metamorphism. The former permeated the conglomerate in such a manner as to form in general a rock that might be called mica schist, but the schist retains its perfect sedimentary structure, and shows multitudes of pebbles of various kinds, many of them of granite. The gabbro formed a rock which has been styled frequently muscovadyte, but still retains boulders, though less distinctly than in the mica schist at Snowbank lake, and rendered the laminated, sedimentary structure much less evident. The ferro-magnesian element of the gabbro has been presumed to have been transferred by heated circulating water in some measure into the older rock, giving rise to hypersthene, biotite and sometimes olivine and enstatite. At the same time a secondary plagioclase is developed, ranging from andesine to labradorite, which embraces, in the same manner as the hypersthene and often as the magnetite, nearly all the other minerals poikilitically. But this hypothetical loss of ferro-magnesian minerals by the gabbro is subject to considerable difficulties, viz.: (a) The ferro-magnesian element in this modified rock is frequently equal to or exceeds the same that would be found in any normal gabbro; (b) The gabbro does not show any noticeable loss of these elements at the points of contact; (c) But rather possesses, as a rule, a greater abundance of these minerals.

Magnetite occurs in abundance locally in this metamorphosed rock. This is the case at Disappointment lake, where it has given rise to exploration for economic results. In some of the annual reports this iron ore was classed with the Animikie. It resembles the iron ores supposed to be Animikie where they have been affected by the gabbro, such as seen at the Gunflint Lake Iron company's works near Gunflint lake, and at Birch lake, but this resemblance is due apparently to the similarity of the original ores and the identity of the rock that caused the metamorphism. The two ores were hematite (occasionally magnetite) with silica as the principal impurity. The action of the gabbro has resulted in the re-formation of both substances, the resulting magnetite serving sometimes as a mesh or sponge in the spaces of which are found grains of secondary quartz and of nearly all the ferro-magnesian minerals of the muscovadyte. This deposit of iron, therefore, is to be parallelized with that existing north of Moose lake, already referred to, found in this conglomerate, rather than with the ore of the Animikie. In a similar manner magnetite belonging in the Lower Keewatin is produced in the green schists. This is found at Garden lake, on the north side of Long lake and near Tower. A belt of magnetite also occurs in the green schists at a couple of miles southwest from Ely. In each case the accompanying gangue rock is quartz in a finely-granular but compact state. It is only in contact with the gabbro that this ore is associated, so far as known, with the ferro-magnesian minerals mentioned at Disappointment lake.

It should be stated here that owing to the sameness of the result of the gabbro contacting on these different ore horizons, whether of the Animikie, the Upper Keewatin or the Lower Keewatin, it is impossible to distinguish them on lithological grounds. The structural environments and the nature of the associated rocks must be taken into account. There is a series of magnetite deposits extending from the vicinity of Iron lake (southwest from Birch lake) eastward as far as to the vicinity of Gunflint lake, which fall into this doubtful category. They occur on the north and south sides of Birch lake, the north side of Thomas lake, the north side of Fraser lake, N. W. ¼ sec. 20, T. 64-6 W., the south side of Gabimichigama lake, along the south side of the stream in the northern part of sec. 35, T. 65-5 W., at Paulson's lake (Gunflint Lake Iron company), and especially about a mile north of the Gunflint Lake Iron company's working, in section 28. The Animikie of the region of Gunflint lake extends unquestionably about two miles west from that lake, at which point it seems to swing southward, the strike of its lowest strata lying in the low, broad valley, which seems to be the northern continuation of the Cross River valley at the point where that river turns eastward to join Gunflint lake. Westward from that vicinity the iron ores above enumerated present ambiguous characters, and there are good reasons for considering some of them metamorphic conditions of lodes of jaspilyte that really belong in the Keewatin. The chief objection to their Animikie age is their intimate association with a rock (muscovadyte) which at Disappointment lake is found to be the product of metamorphism by the gabbro in contact with the Keewatin. These ores, however, in the chapters in volume iv, and on the geological plates, as in all the annual reports, have been represented as of Animikie age. They are as a class the ores which have sometimes been denominated "olivinitic iron ores."* Their accidental occurrence in the presumed line of strike of the base of the Animikie, which here also nearly coincides with the northern limit of the gabbro, was the initial cause of their being grouped with the Animikie. The absence of the black slate of the Animikie in any of its modifications, from the area extending from near Iron lake to within a few miles of Gunflint lake, has been attributed to the overwhelming volume of the gabbro, but it is more than possible that the Animikie never extended so far north, and that all the modified rocks that have been described in this belt, frequently called muscovadyte, as well as the iron ores mentioned, are parts of the Keewatin, chiefly of the greenstone phases. This remark is perhaps to be extended to include the crystalline limestone or breccia of flint embraced in limestone (No. 312), which has been described at Gunflint lake, but not the iron ores nor the horizontal flint seen on the north side of Gunflint lake.

Stratigraphic Structure of the Archean Fragmentals.

The structure of the Archean is made out by the occurrence of conglomerates which indicate stratigraphic breaks in the succession, inasmuch as they contain fragments from the older and not from the later strata. These conglomerates also strike across the structure features of the older series, and frequently dip in marked non-conformity with them. In addition to non-conformities, it has been observed that some of the granitic intrusions are earlier than others, and hence serve as guides in separating the Archean into grand divisions. It has not been found possible as yet to employ thus the ferro-magnesian or basic dikes and other forms of intrusion of the Archean of later date than the basal greenstones, but it is probable that structural and petrographic differences could be discovered to serve such a purpose if a sufficiently extended study and comparison of them should be undertaken.

* *Bulletin vi*, p. 117.

Nomenclature. The following summary sketch shows the succession and the structure of the Archean as made out by the field examinations and corroborated by the petrographical studies. We find no use for the terms Laurentian and Coutchiching as stratigraphic divisions of the Archean, as they seem to be represented, the former by metamorphic and igneous rocks of the Archean, and hence of irregular stratigraphic occurrence, and the latter by metamorphic conditions which are also of different and uncertain horizons. We use the term Keewatin as applicable to all the clastic rocks here put in the Archean in the state of Minnesota, that term having been employed by Lawson for the region of the Lake of the Woods in his Canadian report published in 1886.* At the present time these rocks are all included by the Canadian survey, whether crystalline or fragmental, under the term *Huronian*, and that term would be employed here were it not for the objections brought forward by Lawson, chief of which is that the Huronian of the typical locality, as defined by Logan in his final description,† includes also the Animikie and excludes all mica schists and gneisses. To this may be added the fact that the original definition of the term Huronian embraced under that term also the Keweenawan.‡ By the United States Geological Survey the Archean, so far as it shows evidence of clastic origin, is included in the Algonkian. The crystalline rocks are divided between those which are palpably intrusive in the Algonkian clastics and those which are near the bottom, the latter only being put into the Archean. The term Algonkian might be used, but if due regard be paid to the law of priority it should give place to Keewatin. We divide the Keewatin into two non-conformable parts, separated by a great stratigraphic break. There may be a basal conglomerate at the contact of the fragmentals of the Lower Keewatin on the massive greenstones below, at least in some places, comparable to that which has been described on the south side of lake Superior, but it has not been well identified in Minnesota. Several conglomeratic contacts on the Lower Keewatin have been seen, but in all cases they have proved to be formed by the Upper Keewatin on the Lower.

The Lower Keewatin. The oldest rocks known in the state consist of greenstones. They constitute what has been designated, in some of the annual reports, the *Kawishiwin*. They are both massive and fragmental. As massives they seem to grade into some overlying greenstone beds which manifest clastic characters, the transition rarely having been seen to be that of an erosion interval marked by a basal conglomerate. The only place at which a conglomeratic structure has been identified at this horizon is that described in the Lake county chapter (volume iv, page 292), where a greenstone conglomerate 105 feet thick lies on the massive greenstone. The

* Geological Survey of Canada, New Series, vol. i, 1886.

† Geology of Canada, 1863, pp. 50-57.

‡ *Esquisse Géologique du Canada pour servir à l'intelligence de la carte géologique et de la collection des minéraux économiques envoyées à l'exposition universelle de Paris*, 1855, par W. E. LOGAN et T. STERRY-HUNT.

transition seems rather to have been of the nature of a change from massives to surface lavas and volcanic ash, accompanied in some places by extensive oceanic distribution and sedimentation. These rocks extend east and west in two conspicuous belts. The southern belt begins in the vicinity of Gunflint lake and extends westward by way of Gabemichigamme lake, the Kawishiwi river and White Iron lake to Tower, and indefinitely westward. The greenstone hills, known as Twin peaks, south of Ogishke Muncie lake, are the highest summits of this range. Between Ely and Tower are numerous hills belonging to this range. The northern belt of greenstone enters the state from Hunter's island, appearing conspicuously at the south side of Bassimenan lake. At Pipestone rapids and Fall lake it widens southward and apparently unites at the surface with the southern belt, the overlying Upper Keewatin being absent for the distance of a few miles. But further west it is again divided by the Stuntz conglomerate, the northern arm running to the north of Vermilion lake, west of which its extension is unknown. In general these greenstone ranges constitute topographic elevations, the country being hilly or sub-mountainous, and this character is hightened when granitic intrusion has still further hardened this rock.

It is in the upper part of the Lower Keewatin that occur the iron deposits at Tower and at Ely. The enclosing rock is obscurely characterized, being in the main a greenstone which sometimes is distinctly fragmental, as at Tower, and sometimes hardly distinguishable from a massive igneous one, as at Ely. Owing to the structure and character of the ore, however, which is believed to be of the nature of an oceanic precipitate, it is quite certain that in all cases where this ore occurs the enclosing rock is a sedimentary one, although composed of the elements of a basic eruptive. This ore is common between Tower and Gunflint lake.

The fragmental, stratified portion of the Lower Keewatin becomes more important toward the west, while the plainly massive characters seem to fade away. The southern arm, for instance, of the Lower Keewatin, taking the form of more or less stratified greenwackes and finally of graywackes and argillytes, at Tower widens toward the south and continues apparently to the Giant's range of granite, by the advent of which it is changed to crystalline schists. Westward from Vermilion lake, while it is evident, from what is known of the region, that the Lower Keewatin extends as far as the Mississippi river and its northern tributaries and across the Bowstring river, the prevalence of the drift and the Cretaceous is such that nothing is known as to its divisions and geographic limits. Toward Rainy lake it is also apparent that a similar change takes place, *i. e.*, that the fragmental character prevails over the igneous. In this direction, further, a very extensive regional metamorphism has converted the Lower Keewatin into mica schists and gneisses, and this change has been accompanied by the intrusion of large volumes of granite. It is not possible to affirm that the Upper Keewatin occurs in Minnesota in the Rainy Lake region except at one point, viz., about the head of Jackfish bay, about six miles east of Koochiching. The gold deposits of Rainy lake are in the Lower Keewatin. Between Rainy lake and Kabetogama and Namekan lakes mica schists prevail.

This wide belt of recrystallized fragmentals of the Lower Keewatin probably underlies the most of the central and southwestern part of the state as far as to the Minnesota river, which they cross with a strike nearly at right angles and with a prevalent dip toward the southeast. They run below the later formations in the southwestern counties, but probably occupy, with more or less of intrusive granite, a wide patch in South Dakota. However, in this direction they become covered, both in South Dakota and in Minnesota, by beds of Cretaceous age.

On the south side of the Giant's range of granite, these rocks appear, and here they also carry the same kind of jaspilyte iron ore, but, as the gabbro of that part of the state and the Animikie strata hide them toward the east, and the drift deposits of the St. Louis valley toward the west, their characters and geographic boundaries are mostly unknown. They appear in the central and western portions of Carlton county where their line of separation from the Upper Keewatin is quite obscure. They extend southwestwardly to the central and western portions of Morrison county.

The basic Lower Keewatin or Kawishiwin series of rocks is presumed to be of very wide extent, and perhaps represents the universal original crust of the earth. Its modified clastics and the still later Lower Keewatin graywackes, etc., may be parallelized with some of the gneisses and mica schists which have been included under the terms Laurentian and Coutchiching.

The Lower Keewatin was terminated by an extensive folding and metamorphism, and this movement was accompanied by the oldest known granitic intrusions. These igneous rocks will be considered more in detail at another place, but it is germane to state here that these granitic areas rise as bosses in the midst of the older schists and also penetrate the later greenstones and their attendants as dikes. They vary from indefinite felsitic rocks to quartz-porphyry and to aplitic granite, as dikes, and to coarse granite in larger areas. There are also some indications that some basic rocks of igneous character and intrusive structure date from the Lower Keewatin. Such are certain altered gabbros. The only known occurrences of an Archean gabbro in Minnesota are at a few miles southwest from Motley, in Todd county, and at Little Falls, in Morrison county. There is also an important area of gabbro at Knife lake, on the international boundary, along the southeastern shore, but it is probably of more recent date than the Lower Keewatin. By far the larger part of the granites of the state date from the close of the Lower Keewatin. Such are the granites of Bassimenan lake, of Saganaga lake, a part at least of the Giant's range, and of the region of Rainy lake and the north shores of Vermilion lake. The granites of more southern localities, such as that at Ortonville, at St. Cloud and at Sauk Rapids and in the eastern part of Morrison county, are believed to belong to the same category, because of their association with large areas of highly altered and wholly recrystallized schists that bear the characters of altered northern Lower Keewatin schists. This of course is a character which is very unreliable for such an inference, but it is the only guide to the age of these southern granites which can be invoked.

Marble is also one of the constituents of the Lower Keewatin. It is seen at Ogishke Muncie lake, extending for about four miles conformably with the general structure. From this fact, and from the occurrence of microscopic debris of quartz, feldspar and green hornblende in this marble, it is believed to date from the origin of the rock, and was an oceanic chemical precipitate. A similar marble occurs in the staurolite mica schists at Pike rapids, on the Mississippi.

Upper Keewatin. The rocks which accumulated in the troughs after the folding of the Lower Keewatin consist very largely of conglomerates, but they also include graywackes, quartzytes, argillytes and jaspilytes. Jaspilyte, of the type seen in the Lower Keewatin, is the matrix of the conglomerate on the north side of Moose lake. In the same conglomerate are pebbles of a jaspilyte of an earlier date, and of granite and flint. In favorable locations, as at Ogishke Muncie lake, where this conglomerate lies on the Lower Keewatin, it also contains many boulder masses of diabase and of green and slaty rock similar to some seen in the Lower Keewatin. About Vermilion lake it embraces the Stuntz conglomerate, which is composed largely of pebbles of quartz-porphyry, whose source is probably from dikes of that rock cutting the Lower Keewatin in the near vicinity. At Tower this conglomerate undergoes sudden local variations. It is in some places composed largely of fine green schist, which gradually acquires fine clastic grains and pebbles of jaspilyte (figure 2, plate WW, vol. iv). In the near vicinity this schist is seen to surround larger and larger masses of jaspilyte which attain the dimensions of ten or twenty feet across; and it is very difficult, in such conditions, to distinguish this schist from the green schist underlying from which, as a debris, it has been obtained; and this difficulty is increased by the common folding, pressure and shearing to which they have both been subjected. Beautiful illustrations of this schist containing pebbles and large masses of jaspilyte are to be seen in the "South ridge" at a short distance from the city of Tower, while the original schist, containing the jaspilyte in its native places, can be seen conspicuously in the same ridge, and most prominently in the "North ridge." There is no known general order of succession in the composition of the Upper Keewatin. It can only be said that it is likely to be conglomeratic at the bottom; still that is not always the case, for at Saganaga lake the bottom of the formation is so much like the Saganaga granite (and is really a "recomposed granite") that it has been mistaken in the field for granite by nearly all who have seen it. In other places it appears that a very fine debris from the quartz-porphyries or from the greenstones of the Lower Keewatin has accumulated in the same quiet manner at the base of the Upper Keewatin, the coarser and even conglomeratic composition coming in at a higher horizon. This fact makes it very difficult to establish the precise base of the Upper Keewatin, except where this early fine debris was carried away and the conglomerate lies immediately on the older rock. The Upper Keewatin is cut by granite in the form of dikes and bosses. As it holds granite boulders there must have been an older granite. About Snowbank lake, and also about Moose and Disappointment lakes, it is changed to a mica schist by a regional metamorphism, but only at Snowbank lake is it seen to be penetrated extensively by intrusive dikes of granite. The two most notable masses of the Upper Keewatin are the Stuntz and the Ogishke conglomerates. These are believed to be substantially of the same age, although they are separated by an upward swell in the bottom of the great trough by reason of which they are in isolated areas.

The conditions of rock formation at the time of accumulation of the Upper Keewatin were the same as in Lower Keewatin time, but the detrital forces were much more powerful. It is evident that after the folding of the Lower Keewatin the igneous forces suffered a great abatement, though they did not cease. Isolated volcanic craters continued to throw out volcanic ash, and to charge the atmosphere with acid gases, and the ocean with the same chemical precipitates. This is evinced not only by the occurrence of much of the same volcanic greenstone ash in the rocks, but also by the existence of extensive deposits of jaspilyte in the later schists and conglomerates, as at Moose lake.

The Upper and Lower Keewatin have been subjected to another folding which had a general parallelism with the earlier folding. This pressure was so powerful and the folding so close that the Upper Keewatin lies in narrow synclines in the Lower Keewatin, and in nearly all places its attitude is nearly or quite vertical. With this general statement must be inserted some exceptions, viz., the strike of the bedding suffers sudden local changes. It runs north and south instead of northeast and southwest. Such an exception has been noted on the south shore of Vermilion lake, another on the east side of Disappointment lake (sec. 34, T. 64-8 W.), and still another southeast from Knife lake (secs. 7 and 8, T. 65-6 W). The strike sometimes is even 10° or more to the west of north. Such irregularities have, so far as observed, no systematic occurrence, but still, perhaps, indicate a pressure and a folding tendency oblique to the general direction. They may also be explained by the occurrence of local obstructions such as isolated bosses of the older formation round which, to some extent, the later strata tended to be warped within narrow limits.

This later folding was accompanied by metamorphism. The Upper Keewatin is converted to a micaceous rock about Snowbank and Moose lakes, and the Lower Keewatin (?) to a muscovadyte about the southern confines of Disappointment lake. These rocks are so similar to those produced by metamorphism of the Lower Keewatin that on petrographic grounds they cannot be distinguished. Still, it is plain that the rocks of the Upper Keewatin, in all known instances of such metamorphism, retain more of their clastic characters than do those of the Lower Keewatin.

[NOTE. There is an element of uncertainty in the assignment of rocks about Moose lake which contain the jaspilyte already noted to the Upper Keewatin; and this uncertainty is to be extended to the mica schists about Snowbank lake and the muscovadyte about Disappointment lake. The difference in metamorphism and the conglomeratic composition are features that might still inhere in the Lower Keewatin, and the general geographic position of these lakes rather favors the Lower Keewatin age of the surrounding schists and the jaspilytes. Their strongest Upper Keewatin character consists in the occurrence of pebbles of older jaspilyte and of granite in this conglomerate. This implies that some older terrane, probably the Lower Keewatin, had been formed, folded and cut by granite prior to the creation of these strata, for we know of no granite nor jaspilyte older than the Lower Keewatin.]

THE IGNEOUS ROCKS OF THE ARCHEAN.

Nature of the Archean igneous rocks. The igneous rocks of the Archean consist of two grand divisions, viz.: the massive greenstones and the granites, of which the greenstones are the older. With this grand distinction recognized, it is still true that there are a few intermediate rocks, but these are so small in amount that they are not worthy of class designation, and are so doubtful as to genesis that it is best not to include them in a fundamental classification. They will, however, be treated in a separate paragraph. There are also numerous dikes which are both granitic and diabasic. The former are included in the Archean, but of the diabasic dikes a considerable number are of later, probably Keweenawan, age.

The Archean greenstones show by their state of alteration that they are very old. Their original crystalline characters are much obscured, and sometimes quite obliterated. They are intimately associated with fragmental rocks that consist almost wholly of the same minerals as the greenstones, and these fragmental rocks have undergone such pressure and consolidation that in some instances they are very similar to the crushed massive greenstones, and the whole mass has frequently been classed as a unit under the designation Kawishiwin, a name derived from the Kawishiwi river, on which these rocks are well exposed. The petrographic characters of these rocks are given in another chapter, and their outward characters in the special chapters descriptive of the geological plates in volume iv.

That these rocks are older than the oldest known granite is shown by the apophyses from the granite which penetrate them. Such are to be seen wherever the two rocks approach each other, but may be specially mentioned at the northwest end of Birch lake, at the west side of White Iron lake, on the Kawishiwi river and at West Seagull lake. When the granite is in large masses the greenstones are metamorphosed by general and dynamic forces and converted to hornblende schists and amphibolytes. This alteration is not due so much to actual contact of the granite as to some deep-seated and widespread force acting on the older rocks over extended areas at the time of the granite intrusion. The older rocks seem to have been nearly at the same temperature as the intrusive rock, since the dikes do not generally show the structure due to chilling along their borders. When such dikes, however, are remote from the centres of metamorphism they are seen to be chilled at their borders.

As the greenstones merge into more and more clastic and siliceous rocks, as seen about the Twin peaks, and at the northwestern confines of Vermilion lake, and at Rainy lake, such widespread metamorphism gives rise to banded gneissic rocks of varying composition, sometimes quite hornblendic and sometimes quite siliceous, and in this form the upper part of the Kawishiwin has apparently been extensively altered into a group of rocks (gneisses, mica schists, etc.), which have very generally been taken to be the oldest known rocks of the earth's crust.

Besides these basal greenstones and their attendants, of the age of the Lower Keewatin, there are similar greenstones in the Upper Keewatin. These, however, differ from the older in being in general more plainly fragmental, and often in containing coarse fragmental debris. These fragmental beds are, in part at least, the rocks sometimes called "slate congomerates." They contain sometimes large pebbles of diabase and of granite, and often are distinctly bedded, making, when they become finer, graywackes, slates and quartzytes. That volcanic action was continuous into the Upper Keewatin, in northern Minnesota, is in harmony with all the structural and petrographic phenomena of the Upper Keewatin rocks, but exactly where the vents of volcanic ejection existed, it is at present impossible to state. It is probable that the volcanic areas of Lower Keewatin time would some of them be perpetuated into Upper Keewatin time, the intervening revolution not being sufficient to permanently obstruct the old ducts. It is hence also probable that it would be very difficult to divide the greenstones produced by such prolonged action in the near vicinity of such vent, into two epochs comparable to the two epochs into which the Keewatin fragmentals are divided. The region of the Twin peaks south from Ogishke Muncie lake is likely to be the seat of a long continued volcanic vent. Another seems to have existed about the northeastern confines of Kekequabic lake, and still another about the eastern end of Otter Track lake on the international boundary.

The granites of the Archean are well known. Several are described in later chapters in this volume, and their structural relations to the schists, gneisses and greenstones are given in the special chapters of volume iv. These granites are of at least two dates. As already stated, one series cuts the Lower Keewatin only, and the other cuts the Upper Keewatin. In numerous instances have been seen two series of granitic dikes, in the same rock, one series cutting the other. This occurs north of Vermilion lake, and at West Seagull lake. It is, of course, not known that these represent the two principal granitic epochs of the state, but it may be assumed.

The granites are more variable than the greenstones. They vary in texture and in composition; yet, as a whole, are better preserved than the greenstones. They very rarely show the effects of dynamic action, while the greenstones are frequently converted to schistose rocks by such action. The coarsest granites (aside from pegmatitic veins) are those of Saganaga lake, in which the quartzes are sometimes nearly half an inch in diameter, and are distributed evenly throughout the rock, and of Ortonville, in which the feldspars, orthoclase and microcline, are porphyritic, and sometimes are an inch and a half in larger dimension. A similar coarsely porphyritic granite occurs in Stearns county. The granites sometimes become gneissic. This word may be taken in two senses, viz.: the granite may become foliated by the occurrence of divisional planes, along which are a few more mica scales than elsewhere, but which do not affect the megascopic aspect, except on weathering. These divisional planes are separated from two to four inches. This rock, when quarried, appears massive and homogeneous. It is frequently seen at Bassimenan lake. Another form of igneous gneiss is that in which the minerals and even the mass of the rock are elongated uniformly in one direction, but in an interlocking mesh, making still a massive and nearly homogeneous rock, but on quarrying, having a distinct rift in one direction. These variations in the massive granites should not be confounded with the banding of the true gneisses derived from the metamorphism of sedimentary beds, which constitute probably seventy-five per cent of the gneissic rocks of the state.

The chemical composition varies in such a way that the alkali present is soda, as well as potash, making soda granites, or soda syenytes when the quartz is wanting. Frequently, also, the Archean granites contain some of the soda-lime feldspars, and they then pass into diorytes and to quartz diorytes. Rarely augite takes the place, in part, of hornblende, and still more rarely fluorite is found. Commensurate with these variations the rock takes different aspects, sometimes becoming quite dark with hornblende and biotite, and sometimes nearly white, because of the absence or scarcity of those minerals.

Distribution of the Archean granites. Owing to the fact that the granites graduate into gneisses, and that gneiss, which graduates into mica schist, may be of igneous or of aqueous origin, it is a priori impossible to indicate precisely the limits of the Archean granites. To this statement it should be added that no attempt has been made to outline the granites, either in the field-work or on the plates of vol. iv which show the areal geology. Considerable areas of the northern part of the state have not been traversed with sufficient frequency to furnish such information. It has only been ascertained that in such areas the rocks in general pertain to the crystalline series, and a single division has been made, viz.: into schists and gneisses, and the igneous granites have been included with the gneisses. In general, however, it is true that large areas of Archean igneous granitic rock cross the northern part of the state, trending with the grand features in a northeasterly direction. The Giant's range is the most southerly of these belts. This forms the most abrupt Archean hill-range in the state, running for the distance of fifty miles and maintaining the prominence and often the sharp outline which simulates that of a great protruding dike. Toward the north this granite spreads over the lower ground and disappears under a sheet of drift so effectually that its northern limit is wholly conjectural. This sudden change in topographic aspect suggests that the elevated belt is of a different date from the low ground granite, and is perhaps of later date. The Animikie lies in a tilted position on the southern slope of the Giant's range in its dike-like form, as if it had been uplifted by the intrusion of that granite.

Toward the northeast this belt of granite, after some interruption, is certainly, in part at least, of Lower Keewatin age, as it supplied debris to the Upper Keewatin conglomerates. This can be seen at the Kekequabic and Saganaga lakes, while at Snowbank lake the granite of the region cuts the Upper Keewatin.

The central islands and the southern shores of Bassimenan lake also consist of the earlier granite, which seems to be continuous with the granite of the northern shores of Burntside and Vermilion lakes, and with that of the international boundary at Lac la Croix and Kabetogama. About the southern confines of Rainy lake, granite gives place to much gneiss and schist. Granites are known in the central and southwestern counties, as in Morrison, Stearns, Benton, Todd, Big Stone, Nicollet, Redwood, etc., but the extent of these areas is unknown, owing to the prevalence of the drift.

Genesis of the Archean igneous rocks. The greenstones. The massive igneous portions of the Lower Keewatin, the oldest known rocks in the state, are believed to represent the first magma of the earth, and hence they are referable to the first cooled crust that enveloped the molten mass.

The question of the origin, as well as the order, of the Archean rocks has given birth to much discussion, for it is one of fundamental importance. Much of the diversity of opinion seems to have sprung from a defective and sometimes from an erroneous idea of the rocks themselves, and from differences in the usage of terms. The whole group of rock masses that lie below the basal conglomerate of the Taconic has been discussed as if it were a unit in structure and origin, as well as in date. Under the general term "crystalline rocks," they have been supposed to be due to original congealation of the surface of the earth, or to the crenitic action of water. At one time they have been assigned to a metamorphic origin, from sediments, and again considered as original precipitates in their present mineralogical constitution from a peculiar primeval ocean, a chaotic liquid which surrounded the globe, holding them as silicates in solution. By some extensive volcanic action has been invoked and by others specially excluded.

The following historic sketch of the progress of opinion is essentially condensed from T. Sterry Hunt,* the author of the "crenitic hypothesis," but with additions.

Newton, Descartes, Leibnitz, Buffon and others, seeing a resemblance between consolidated volcanic rocks and some of the crystalline rocks, and assuming a former molten condition of the globe. inferred that the crystalline rocks, whether massive or schistose, were the cooled and consolidated outer crust of the globe.

Lehmann (1756), called them "primitive," and regarded them as "parts of the original nucleus of the globe," which had not been altered since. Pallas and De Luc had the same opinion, though De Luc lastly admitted that they are due to "aqueous deposition." Pallas also regarded them as "due to the agency of water," and believed that volcanic phenomena were but "local accidents" (1777).

According to Werner (1785), "the crystalline rocks" were separated from the primeval ocean as chemical precipitates, and granite was the first laid down. This was followed by the gneisses and the mica schists. Thus Werner accounted also for basalt, and all the forms of the Archean. He saw no indications in these rocks of volcanic activity, or of subterranean heat. Actual volcanoes were by him explained as caused by internal combustion of carbonaceous deposits.

According to Hutton (1785), and Playfair, his interpreter (1802), who argued from injected granitic veins and from analogies with basalts and volcanic rocks, granite is of igneous origin, cooled from fusion. He supposed that quartz, feldspar, tourmaline and other minerals in granitic veins are formed from cooling from igneous fluidity. But Hutton considered granite of later date than the strata that lie on it, agreeing, however, with Werner that granite is the lowest known rock. Hutton, however, considered the gneisses and the schists as of different origin, viz.: detrital, distributed by water, consolidated by heat and by pressure, re-fused, injected in the strata, destroyed and again re-formed by the same process, in a ceaseless round, without beginning or end. He was attacked by theologians, and Werner's hypothesis, which began in chaos and invoked a universal ocean, was espoused by them. Wernerism, however, could not withstand the evidences of observation,

*HUNT. *Mineral Physiology and Physiography*, pp. 68-115.

showing that trappean and other rocks in a heated and fluid state had been injected, and Huttonianism prevailed largely.

De la Beche (1837) urged a modified neptunian (Wernerian) hypothesis, viz.: an unoxidized nucleus, a solid crust resting on a liquid interior, and a primeval ocean, gradually settling from the atmosphere as the crust became cool enough; and came to the conclusion that the stratified igneous rocks resulted from chemical precipitation from such an ocean. These would be mingled, more or less, with the products of direct igneous action, and often no lines of demarkation could be drawn between them.

Daubrée (1860) adopted and amplified the view of De la Beche and enforced it by experimental tests of crystallization of silicates under pressure in the presence of the vapor of water. Daubrée presumes that when the surface passed from the dominion of fire to that of water, it experienced a long series of chemical conditions promoting many decompositions and recompositions, aqueous action intervening with igneous, and again giving way before it, during which two principal products (structures) would be formed, one massive and the other sedimentary, passing into each other gradually. The crystallization of the silicates must have taken place in the presence of watery vapor. This vapor was under tension of 250 atmospheres, and a temperature of about 1330° centigrade "about that of redness." Thus Daubrée adjusted the Wernerian hypothesis to the theory of La Place of a fused and cooling globe, and supplied the "chaotic liquid," or universal ocean required by the Wernerian hypothesis.

In all these hypotheses the primeval rock is granite. Werner, Hutton, Macculloch and Elie de Beaumont supposed the first crystalline rock to have been that of granite, and Scrope imagined the whole earth to have separated from the sun as an irregular, granitic aerolite, on which were subsequently formed the gneisses and schists by the action of the primeval ocean, mainly through a process of disintegration and of regeneration. The process of sedimentation for the gneisses and schists though opposed by Saussure, was approved by Hutton, Boué and Naumann, and came to be generally believed.

Hence, when Lyell (1833) proposed the theory of metamorphism, giving origin to the hypogene metamorphic rocks (gneisses and schists) by a deep-seated change in the detritus from the first granitic crust, it was readily accepted, and has remained in vogue to the present time.

This theory, however, as it requires the destruction of a vast amount of the original granitic subcrust in order to form the 30,000 feet, more or less, of the gneisses and schists, met with a physical difficulty. It requires at once sufficient elevation of the granitic crust to bring it into contact with erosive agents, and a submergence below the ocean to allow of the enormous accumulations. This difficulty was met in part by Dana (1843), who introduced and amplified the idea of volcanic origin of much of the materials of the metamorphic rocks. He claimed that most of the crystalline igneous rocks could be formed also by the recrystallization of their debris, and that in the vicinity of volcanoes such debris was always abundant. According to Dana, pyroclastic material enters largely into the constitution of the "hypogene metamorphic rocks" of Lyell.

Clarence King (1878) recognized volcanic action as a source of oceanic debris, but showed that great depth alone (30,000 feet) is not a cause of metamorphism. He explained the origin of olivine rocks, magnesian silicates and serpentine, by the occurrence of volcanic olivine sand, etc. King also accounted for the variations seen in igneous rocks, by a process entirely novel. He assumed the downward increase in density of the mass of the earth, solid from pressure, and ascribed to removal of pressure the occurrence of fused areas or lakes of lava. As these were liable to occur at varying depths they would issue at the surface with the characters proper to their various densities, and would be local and temporary. By this, and by a presumed separation of such molten lakes through the action of gravity, into two parts or layers, the more dense at the bottom, all the varieties of igneous rock are explained.

Marr (1883) urged the volcanic source for the origin of the ancient crystalline rocks, *i. e.*, the gneisses and schists, and this element has been admitted more and more to the present day, except by T. Sterry Hunt.

Dr. Hunt proposed (1884) the "crenitic hypothesis," for the origin of granite, gneiss and all the other Archean rocks, including the schists, basalts and greenstones. This hypothesis conceives the crystalline rocks to have been derived, directly or indirectly, by solution from a primary stratum of basic rock, the last congealed and superficial portion of the cooling globe, through the intervention of circulating subterranean waters, by which the mineral elements were brought to the surface. This circulation is supposed to have been caused by heat from below and surface radiation. It is noteworthy that this hypothesis presumes a primeval basic layer, which is wholly lost by the crenitic process, originally not differing much from the composition of doleryte, and yet appeals to the "Huronian greenstones" as one of the products of the crenitic action, the last step in the process.

As metamorphism came to be recognized by most geologists as an essential element in this investigation, the question assumed two branches, viz.: the origin of the materials of the crystalline stratified rocks, and the origin of the differences in the igneous rocks. On the latter, recent investigation has been centered, under the terms segmentation or differentiation of magmas and their succession. At the same time much more accurate knowledge has been reached as to the nature and succession of all the parts of the crystalline rocks. The study of the igneous rocks proper since this division of the inquiry has been conducted by Rosenbusch, Teall, Iddings, Brögger, Michel Lévy, Geikie, Becke, La Croix, Lang, Lewinson-Lessing and others. The examination of the order of succession of the Archean rock masses has been carried on chiefly in the United States by the officers of the U. S. Geol. Survey, and of some of the state surveys.

On theoretical grounds, Dolomieu maintained, in the latter part of the last century, the existence, "beneath the granitic substratum, of a liquid layer which gives origin to basic rocks and lavas. A similar view was developed later by Phillips, Durocher, Bunsen and Streng, "who have imagined a separation of the liquid layer, or the matter at the surface of the cooling globe, into two layers, an upper acidic one corresponding to granites and trachytes, in which, besides alumina and an excess of silica, lime, magnesia and iron oxide are present in very small quantities, and potash and soda abound; and a lower basic one corresponding to doleryte and basalt, in which lime, magnesia and iron oxide abound with an excess of alumina, and but little alkali." These two constitute the trachytic and pyroxenic magmas of Bunsen, who derived his ideas (1851) from a prolonged study of the volcanoes of Iceland. Bunsen also believed that various intermediate rocks are produced by a mingling in different proportions of these two separated magmas.

Waltershausen (1853) criticised Bunsen's conclusions and maintained that while there is no distinct separation into basic and acidic magmas, there is still a gradual passage downward from acidic to basic, even increasing to a metallic interior with the metals and minerals arranged according to their densities. This was adopted and extended by Macfarlane (1864), and approved by Richthofen and by Zirkel (1866). According to this theory the earliest igneous eruptions were not of basic character, but came from near the exterior, and were feldspathic. Later igneous rocks became progressively more basic, coming from deeper and deeper reservoirs where the more basic elements reside, thus accounting for the basic nature of the late eruptions.

Von Cotta (1858) proposed the idea that below the siliceous crust, made up of granites, gneisses, etc., there exists a mass of more basic rock material mainly in the state of fusion, and that this sub-crust mass is the source of the basic eruptives. These eruptives become modified by the incorporation of more or less of the acid crust in the process of extrusion.

Durocher (1857) also shows the existence of two distinct magmas, one acid and one basic, and that intermediate rocks of eruptive origin are due to contact and mingling of these two magmas. Gravity determines the relative positions of these magmas, the basic being below the acidic.

Jukes on the other hand (1862) assumes a generally diffused uniform molten mass, from which, by a process of segregation, the basic rocks are extracted under certain conditions, and acid ones under others. This is essentially the idea of Iddings, which (1892) has been discussed by him under the topic of "Consanguinity" of igneous rocks.

Dutton (1880) assumed a primordial basic primitive crust, allied to basalt or doleryte, entirely homogeneous, and appealed to atmospheric forces to separate from it the more acid parts and form of them the quartzytes, granites and gneisses. The sedimentary products of erosion are heterogeneous, and by the rising of temperature within certain subterranean horizons, or perhaps by relief of pressure, the deeply buried materials are re-fused, to issue as igneous rock at the surface, with their recognized heterogeneous characters; or are reconsolidated *in situ*.

Under various theories for the cause of such differentiation, if it exist, this investigation has been carried on by Rosenburch (1889), who maintains that beneath the earth's solid crust the molten interior is separated naturally into certain reservoirs or "kerns" in which are gathered different magmas of which he distinguishes, on chemical grounds, five classes; by Brögger (1890), who believes that on account of the principle of Soret, certain silicates more basic than those with which they are associated are concentrated upon the borders of laccolitic masses, and hence are also the first to appear in cases of extrusion, followed by the magmas more acid; by Iddings (1892), who considers the differentiation to be caused by physico-chemical forces, largely inherent in the environment of the supposed primary or fundamental magma; by Geo. F. Becker (1897), who demonstrates that if such segmentations have occurred under the operation of physico-chemical forces, the time involved is inconceivably long, and the process so slow that fifty millions of years, or all the time elapsed since the close of the Archean, would be insufficient, and that the probable direction of the action of osmotic force would be to promote uniformity rather than heterogeneity; by Michel Lévy (1897), who, questioning the actuality of such differentiation and noting the opposing tendency of numerous observed facts, reaches the conclusion, from an exhaustive comparison of the chemical constitution of rocks having the "air of family," that but two magmas of permanent and fundamental importance can be recognized, viz., a basic or ferromagnesian one, and an alkaline one, represented respectively by diabase and granite. Of these, Michel Lévy finds the ferromagnesian was the earlier, and that from it, by a process similar to the "crenitic" of Hunt, the alkaline magma may have been produced, the basic lying below the alkaline. He, however, supposes the transformation took place in deep-seated reservoirs before solidification.*

*Classification des magmas des roches éruptives. *Bulletin Société Geologique de France*, xxv, 326, 1897.

It is a remarkable fact that, although several geologists have assumed a primordial ferro-magnesian rock as the earliest condition of solidified matter on the cooling globe, not one has been able to indicate a spot where it can be seen, but have assumed that the oldest known rock is a granitic or alkaline one. Hutton originally pointed out that this granite is younger than the strata that lie upon it, and Lawson has shown* conclusively that it breaks through the mica schists and the fragmental rocks of the Keewatin. As already fully stated, this is also the case in Minnesota, and it follows that the oldest rock at the surface cannot be these eruptive granites, whatever may have been their origin.

Those who have followed this chapter from the beginning will have learned that this granite is also more recent than that great greenstone series which plays so important a part in the geology of the Lake Superior region. They will also have noted that between the date of origin of the massive greenstones and the granitic intrusion there was formed an important series of detrital rocks, and that these detrital rocks, very largely composed of volcanic ash and to some extent of oceanic precipitates, such as silica, oxide of iron and lime, have been metamorphosed into the mica schists and gneisses which are cut by these granites. In other words, between the origination of the greenstones and the intrusion of the granite there was an immense lapse of time, which was characterized by a widespread, if not by a universal, scene of vulcanian activity. These volcanoes were, as indicated by the generally stratiform condition of these fragmentals, closely surrounded by the primeval ocean into which their ejectamenta fell,† and its erosion products must have mingled with the volcanic to constitute the cotemporary strata. Such strata would necessarily sometimes be acid and alkaline, and sometimes irony and magnesian, and would have embraced any oceanic chemical precipitates.

Origin of the Archean granites. Recent careful studies of the Archean granites have demonstrated several important facts respecting their nature and structural relations, showing their intimate connection with the gneisses, and thence with the mica schists. Before, however, mentioning these bonds of affinity, it will be best to refer briefly to some ideas that have lately been promulgated concerning their origin.

Relying on the result reached theoretically by numerous petrographers and upon the observed fact that, in Minnesota, the "greenstones" are the oldest of the Archean rocks, we are at once brought to the consideration of the question of the possible derivation of the granites from the greenstones by some process of alteration or differentiation.

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*Geology of the Lake of the Woods. *Geological Survey of Canada*, 1886.

†The Kawishiwin agglomerate at Ely, Minn. *American Geologist*, vol. ix, pp. 359-368, 1892. In this paper, and in others written in the course of the prosecution of the geological survey, the greenstones were erroneously assumed to have been later than the granites and gneisses, following the order established by the Canadian Geological Survey.

It has been presumed by Hunt that by a long period of lixiviation by circulating waters the elements of the granite, as well as of all the other later crystalline rocks, were extracted from the early doleritic crust and brought to the surface and deposited in such form that they constituted, on consolidation, the rocks under consideration. By an extended series of chemical and mineralogical examinations he finds that all the minerals of the granite, etc., are derivable from the early ferromagnesian crust, by the long-continued forces which he advocates. Recent researches by Michel Lévy also indicate that, starting with the ferro-magnesian scoria or outer magma of the earth, represented by some such rock as basalt, there may have been a profound transformation effected in that basic magma, in deep-seated reservoirs, through the action of mineralizing waters circulating through the surrounding rock walls. The end products of this transformation are the alkaline magmas which produce the granites, etc., while intermediate stages in the transformation give rise to igneous magmas of intermediate characters. Michel Lévy also allows for extensive other alteration of the igneous magmas by endomorphous metamorphism, *i. e.*, by the fusion and incorporation of material from the walls of the reservoirs and from the minor openings in the clastic rocks through which the molten masses may pass in their way to the surface.

Against such supposed change from a ferro-magnesian magma to an alkaline one there rises, however, an important obstacle, which appears to be insurmountable. It consists in the fundamental profound chemical difference that exists between these two magmas. It may be admitted, for the moment, that if a process of concentration of certain of the elements of the ferro-magnesian magma be long enough continued, accompanied by a slow extraction of other elements, there would be produced two magmas of contrasted characters. These two rocks, the end products of the supposed differentiation by whatever process, whether at the surface or in deep reservoirs, would contain all the elements of the original magma, and no others. If other elements are found they must be credited to some foreign source. If it be found again that the actual proportions existing between the elements in the derived rock be those that they could not possibly be supplied by the original magma, such excess of some of the elements must also be attributed to some foreign source. Allowing for these considerations, it appears at once that, while there is no potassium in the ferro-magnesian magma, it is the dominating base in the alkaline magma. It must hence have been derived from an extraneous source. It also appears that the amount of silicium present in the derived rock in proportion to that which could be supplied cotemporaneously with the needed quantity of the other elements, such as lime and alumina, is far too great. It is not necessary to enter into extensive or minute comparisons. The single fact that potash could not be supplied by the ferro-magnesian magma, and exists in large amount in the alkaline, is sufficient to warrant a serious doubt as to the actuality of any such transformation.

It has to be admitted that Hunt refers to the secondary occurrence of orthoclase in diabase in the Keweenawan rocks of the region of lake Superior. This he classes with the occurrence of zeolites, which are naturally produced by the first disintegration of the feldspars of the basic rock. Several occurrences of orthoclase and also of quartz in the Keweenawan diabases have been met with by the survey, but in all cases they have been supposed to be due to the inclusion of portions of the clastics within the diabase, or they are so far removed from the first disintegration that they are easily referable to foreign infiltration. Orthoclastic rock in patches is not an uncommon appearance in the Keweenawan diabases at certain points where the diabases are known to be near the clastics, and the inference is natural that where the clastic rock is not visible, the orthoclastic rock has been carried some distance from its source. The following is taken from the sixteenth report, page 16. The petrography of these occurrences is discussed elsewhere:

"It is apparently due to the enlargement and multiplying of the reddish felsitic amygdules (?) locally and the specialization of the mineral ingredients into macroscopical crystals that patches of red rock are produced in this greenstone [at Thessalon, Ont.] No. 1161 represents such red rock. Such patches are sometimes four and even eight feet square, scattered capriciously about, visible on the glaciated surface of the dark rock. This red rock consists apparently of quartz and orthoclase in distinct crystals, embracing in their interstices a greenish to black soft substance that, while finely foliated and resembling chlorite, yet does not seem to have served any other purpose than to occupy the vacancies between the other minerals as they assumed their crystalline shapes. Such nodules and veinings, if not such isolated large masses of reddish granulyte in trap rock, are not very uncommon. They occur at Taylor's Falls and at Duluth, and have been described by the writer at several places in northeastern Minnesota. Since the basic eruptives when in their normal state do not embrace the minerals here differentiated within them, it may be presumed that these exceptions are caused by the local and superficial mingling of small portions of the siliceous supercrust with the heated basic eruptive. On cooling and weathering the supercharge of siliceous matter is rejected from the mass to fill any convenient veins or amygdaloidal cavities that are within reach. When none such are found these crystals are formed within the greenstone, and are uniformly disseminated in it, causing the well known quartz dioryte and orthoclase gabbro."

Other isolated occurrences of orthoclase seem to be due to fumarole action, or at least to the introduction of potash by some later infiltration. On Isle Royale, at the Minong mine, it takes the form of adularia in small crystals implanted on copper (itself a filtration product) and on calcite. The total absence of potassium from normal diabase and hence the impossibility of orthoclase taking source from diabase, is the only point insisted on here. Leucite, which is a potash-bearing mineral of later basalts, has not been discovered in the Keweenawan eruptives nor in the Archean greenstones, nor have any potash-bearing zeolites been reported.

According to the researches of Pumpelly* on the paragenesis of copper and its associates in the lake Superior region, it appears that after the formation of a series of non-alkaline silicates, laumontnite, prehnite and epidote, followed by quartz, there was a concentration of copper in amygdaloidal and other cavities. After the copper and quartz the alkaline silicates appeared, such as analcite (?), apophyllite and ortho-

* *American Journal of Science*, vol. ii, September, October, November, 1871.

clase. If it be legitimate to infer, as has been done by Hunt in support of his crenitic hypothesis, that orthoclase is one of the products of lixiviation from diabase, it is also reasonable to ascribe metallic copper to the same source. On the other hand, it is quite easy to account for all these foreign substances by allowing the action of heated solutions circulating with fumarole activity through the rock long after it was solidified, during the process of cooling, or even at a much later date.*

If the original magma had been of intermediate character, as supposed by Iddings, such differentiation might, perhaps, have produced the contrasted magmas, but that would contravene the first term of the major hypothesis.

In the presence of this difficulty it is evident that some other source ought to be sought for the granitic magma, and for the igneous gneisses. This is not far to seek. Indeed, it is easily demonstrable from two different lines of evidence, viz., (1) Facts of field observation, (2) Facts of petrographic significance. After a brief statement of these two convergent lines of evidence, we shall consider the question of, (3) The source of the characteristic elements of the alkaline magma.

(*1*). *Facts of field observation.* Early in the study of the granitic rocks of Minnesota, the fact of the gradation of the Keewatin rocks such as graywackes, greenwackes, argillytes and sericitic schists, into mica schists, was impressed upon all the field geologists, and such gradation is affirmed in all the annual reports by all the assistant geologists whenever there was occasion to consider that question. Such transitions are found in nearly all cases where a considerable granitic area occurs, the crystalline condition gradually increasing toward the point of granitic intrusion. There are also very extensive areas of mica schists distant from any known granitic intrusion, which led to the conclusion that the crystalline transformation was due to some wider cause than mere contact of granite. Sometimes such mica schists are distinctly from rock originally clastic, containing still numerous boulder forms. This wider operating force has been supposed to be that which is expressed by the term regional metamorphism, and was attributed, in ultimate terms, to a general elevation of the temperature of crust throughout the region affected, either by the approach of large masses of the molten interior toward the surface, or by the heat generated by dynamic movements, or both. A local, temporary settling also might crystallize the fragmentals, by bringing them within the range of higher isotherms. Whatever the special and local cause, there is no question that such transformation is very widespread, and accounts for the greater part of the mica schists, and of the mica hornblende schists.

Equally early in the investigation of the crystalline rocks it was noted that the crystalline schists gradually pass into gneisses. At first a distinction was drawn

*Compare: The origin of the Archean igneous rocks. N. H. WINCHELL, *American Geologist*, vol. xxii, pp. 299-310, 1898.

between those gneisses which are plainly the result of a change in bedded fragmentals, and others which are nearly massive and homogeneous, but only present a gneissoid structure, *i. e.*, a prevailing direction of elongation of the constituent minerals. But it was found that such a distinction, while evident enough at the extremes, could not be maintained, and that the bedded structure gradually loses itself, under varying conditions, and passes into a simply gneissoid structure, the two being parallel and plainly different phases of the same fundamental transformation. In nearly all cases, where such a structural transition takes place it is observable also that there is a corresponding transition in the mineralogical composition, the mass of the rock becoming also more siliceous and alkaline. Indeed, there are considerable areas in the northern part of the state, occupied by crystalline rocks, which would be assigned in mapping by one geologist to the mica schists, and by another to the gneiss and granite, the last two rocks being grouped together according to our uniform practice. There is always evidence of more or less plasticity and of bodily movement of masses of the rock, and of streaming out of all the original structures, in the vicinity of transitions from the schist to igneous gneiss.

That the gneiss here referred to, *i. e.*, that which is massive, with only a mineralogical gneissoid structure or but rare and confused schistosity, is traceable into true granite, is a well-known fact of field observation, which has been repeated by numerous geologists. There is on this point very little, if any, difference of opinion.

When the crystallized fragmentals are dark colored, with larger amounts of mica and hornblende, the resultant gneiss or granite is also darker, but seems to differ in no way as to genesis and structure, from the lighter-colored crystalline rocks. They differ only in holding larger amounts of the dark minerals, and in their proportionate amount of quartz. In such instances the massive rock is rather dioryte than granite, and may be syenyte; and in some instances all stages of transition from one rock to the other can be collected within a comparatively small area.

(2). Facts of petrographic significance. As a group these rocks, from mica schist to granite, are characterized by much silica and varying amounts of alkaline feldspars. They rarely acquire hornblende or pyroxene and biotite in sufficient amount to warrant the adjective *basic*.* When these minerals do exist in consider-

*The recent investigations of Dr. F. D. Adams on the chemical composition of certain gneisses of the province of Quebec,† have a bearing on this point. He has compared the chemical composition of several gneisses with that of a gneiss from Trembling mountain, and a granite from Carlingford, Ireland, these standards being assumed as normal igneous rocks. He finds that the gneisses investigated, while having a higher content of alumina than the assumed standards, a lower per cent of alkalies and a preponderance of magnesia over lime, have a chemical resemblance to certain clay slates and quartzytes. One of the gneisses of the series investigated has an intermediate character, its magnesia prevailing over its lime, so that it is "impossible to draw from its chemical composition any definite conclusions as to its origin. It might be an altered sediment or an altered igneous rock, or a sediment of the nature of a tuffaceous deposit." Dr. Adams concludes that the other gneisses of this series may be considered highly altered conditions of ancient sediments.

These are important results. It might be asked, however, what has determined the standard composition of an igneous rock, and whether the distinguishing chemical characters accepted by Adams will not be found to vanish when the comparison is extended so as to include undoubted igneous rocks from other localities. This seems quite possible from the fact that one of the selected gneisses of Dr. Adams' series is pyroxenic, and manifests such intermediate characters that it is to be considered as possibly "an altered igneous rock." The gneisses selected are interstratified in limestones and quartzytes so metamorphosed as

†Laurentian area to the north and west of St. Jerome. *Geological Survey of Canada*, vii, 1894 [1896], Report J, pp. 93-112.

able amount the massive rock acquires other names, such as amphibolyte, or eclogyte, and when free quartz disappears they vary to dioryte or syenyte; and as syenyte they still vary to laurvikyte when orthoclase is abundant and soda-bearing; to monzonyte when the feldspars are both alkaline and soda-lime-bearing and the rock contains augite; nordmarkyte when they contain more or less microperthyte of orthoclase and oligoclase, quartz and small quantities of biotite, pyroxene, hornblende and ægirine; pulaskyte, which consists of orthoclase in kryptoperthyte forms, hornblende, biotite, diopside, eleolite, sodalite and accessory minerals; shonkinyte when they consist essentially of augite and orthoclase; and yogoyte when orthoclase and augite are in about equal amounts. When free quartz remains there has been a similar multiplication of nomenclature as the other ingredients vary. It is not necessary to enumerate these minor variations. They testify to constant fluctuation in the chemical composition, all implying a similar variation in the source from which they are derived. They point to the addition of potash and silica, in constantly varying amounts, to the elements already present in the ferro-magnesian rocks.

There are microscopical characters which should be noted, indicating a progressive crystallization in the fragmentals, leading up to structures that cannot be distinguished from those of massive granites. This is not intended as a general statement simply, for it is so well known that it need not be repeated; but as a fact of special and local observation in an individual rock mass, where the fragmental rock mass manifestly furnishes the material for the intrusive granite, which cuts it. In the field such relations are easily inferred from the study of the major structures* and such transitions have been tentatively assumed in some of the earlier publications. It was not until the rocks collected could be examined in detail that the petrographic transition could be seen to accompany and confirm the structural transitions. But one instance has been fully investigated. It is that of the granite of Kekequabic lake. The details of the petrographic examinations are included in the chapter devoted to the petrographic geology, and the field structures are presented in the chapters descriptive of plates 68 and 80. The evidence may be summarized as follows:

The Kekequabic granite. There is a small area of a reddish-gray gneissoid granite rising dome-like in the midst of the Keewatin. The clastic strata adjacent consist of a siliceous actinolitic schist, in general terms, but it varies in different ways. The hornblendic element becomes coarser and the rock assumes the character of a pecul-

to have no more clastic microscopical character than the gneisses themselves. It is not improbable that if a block analysis could be made of the whole mass, including both gneisses and evident fragmentals, the resulting composition would not vary strikingly from that of the gneiss of Trembling mountain, or from that of the granite of Carlingford. Indeed, if the whole seven analyses given by Dr. Adams, both slates and gneisses, be averaged, the result is: silica, 64.85; alumina, 15.74; lime, 1.55; magnesia, 2.94; soda, 1.39; potassa, 3.75, which does not vary much from a normal granite. If to these could be added the lime and quartz of the strata excluded by the selection of sedimentary gneisses only, the result would certainly not fall far from the composition of the normal igneous gneiss of Trembling mountain.

*Some new features in the Geology of Northeastern Minnesota. *American Geologist*, xx, July, 1897, pp. 41-51.

iar hornblende porphyry (No. 741). At other times the hornblende is partly replaced by augite, which is allied to ægyrine and in nearly all cases it can be seen to have been derived from augite by a uralitic (?) alteration. This derivation is evinced chiefly by a particolored polarization which sometimes represents exactly the original crystal form of idiomorphic augite, surrounded by fringes or external growths beyond the augite limits. When the augite grains were fragmentary, or were corroded before being enclosed in this rock, the hornblendic growths have exactly filled them out, the dark color of the polarization (or even the color seen in ordinary light) showing distinctly the original augitic outlines. Besides the conspicuous hornblendes sometimes this schist contains traces of feldspars, but usually feldspar is not evident. When feldspar is seen, the crystals often appear to have been altered into a microgranulitic mass of secondary grains which appear to be of quartz and feldspar. Sometimes pellet-like spots appears under the microscope, which are occupied by such granulation. By their assuming in thin section distinctly lighter and darker aspects four times in one revolution of the stage they are plainly due to a replacement of an old feldspar whose substance and crystalline integrity are not entirely lost. The "groundmass" containing these altered crystals is composed largely of finer condition of the same elements, but usually it embraces a notable amount of quartz. This quartz is in the form of free grains, of angular clastic shapes, or it is very fine and intimately interlocked with equally fine grains of feldspar.

This green schist is sometimes composed almost wholly of actinolite spicules. At other places it passes into a greenish graywacke. It is distinctly a fragmental rock, and shows a coarse, even pebbly, structure, the pebbles being usually of rock like itself, but finer grained. It is also distinctly bedded by sedimentation. It is considered to be largely of the nature of a volcanic tuff, and grades into the greenstones of the surrounding region supposed to be Upper Keewatin. This rock is represented by many numbers, of which the following may be mentioned: Nos. 1409, 1411, 1412, 1413, 1768, 1049, 1050, 1055, 1057, 1060.

This schist is part of a large sedimentary series, passing through greenwacke and graywacke into a pebbly conglomerate with which it intergrades. This conglomeratic condition is sometimes specked with coarse white feldspars, when it has been called *porphyrel*, and is well exposed in its perfect development at Zeta lake, east of Kekequabic lake. This "porphyritic" aspect, however, is widespread and sometimes appears in rock which is plainly fragmental though not conglomeratic, and has been noted especially in the region between Moose and Snowbank lakes.

The intrusive rock is sometimes a granite and forms distinct dikes cutting the schist and its associates, and sometimes is a porphyry, forming knobs of small dimensions that swell up rather fortuitously in the schists. As knobs this porphyry is known to occur beneath the schists and also superimposed on them, but it is not known, in this region, to occur as dikes in the schist, although it cuts some of the associated clastic strata. The granite also rises in domes though considerably larger. Geographically the porphyritic domes are so situated in relation to the granitic areas that they can be considered peripheral phases of the granite, projecting further amongst the clastics than the granite proper, but they were probably derived from slightly different sources.

Both the granite, which also passes into syenyte, and the porphyry, contain in places numerous pebbly or bouldery inclusions, and in the field have been noted several instances where megascopically the crystalline rock passes into the pebbly green schist already described, and into a granite which is charged with pebbles. These transitions seem to be in accord with microscopic transitions, as detailed below.

In the first place, it should be noted that there is a striking mineralogical affinity between the schist conglomerate and the crystalline rock, in that the augite in both is ægyrine, and that the feldspars of the schist-conglomerate, having very striking and unusual characters, are duplicated in the porphyry and in the granite, *i. e.*, the original feldspars are remarkably twinned and zoned. This statement as to the augite is not demonstrated, but rests on the concurrent evidence of other microscopic characters. It is evident that in such a schist it would be almost impossible to find augite retaining its crystalline form, for it readily changes to hornblende, that being indeed almost the first mineralogic change that takes place in a volcanic tuff of such age. But the augitic cores remain in the schist, sometimes as augite (No. 1060), and, on a still broader scale, the original forms of the augites are outlined in the resultant hornblendes by differences of absorption and of colors between the nicols. Exactly the same characters are seen in the augites of the porphyry where the preservation is sufficiently perfect to disclose the ægyrine characters of the original augite. As to the sameness of the feldspars, with their peculiarities, there is no question.

These two important characters ally these rocks in some way in a genetic bond, for the feldspars especially are wholly unlike any known elsewhere in the state. Chemical analysis points to anorthoclase, but the zoned structure, when analyzed by the microscope, indicates that the feldspars began as labradorite, passed to andesine, and sometimes at least terminated as albite, there having been a continual increase in the acidity of the material from which they were generated.

The general aspect of the granite (seen in thin section) along the south side of Kekequabic lake is suggestive, not of crystallization from a magma, but of simple induration of coarse debris. The feldspar grains do not interlock, except as they have been enlarged by a secondary growth, and in many sections examined they do not even come into contact, but are separated, very generally, by a space which is occupied by a fine interlocked secondary development of feldspar and quartz. The margins of the feldspars frequently are interlocked in this new growth. As this fine matrix increases in amount so the rock becomes porphyritic; as it increases in coarseness so the rock becomes granitic, but in all cases, or in nearly all, there is a distinct difference between the old feldspars and the new (compare rocks Nos. 1100 and 1101). Along with this generation of new feldspathic material is also the recrystallization of the quartz, thus making a truly granitic rock. The old feldspars, which, in the clastics proper, without metamorphism, have a tendency to disappear by a process of micro-granulitization into a fine mesh of secondary feldspar and quartz resembling the surrounding matrix, are by metamorphism regenerated by new borders and by micro-granitic growths of coarser grain, and by these new growths interlock about their margins. Occasionally the old feldspars embrace and surround idiomorphic small crystals of augite, having taken that relation in the magma in which they were generated, but the later feldspars do not enclose augite in that way. When the fragmental augites are not altered to hornblende, which alteration is usual, they are simply embraced between the newly developed feldspars. The old feldspars, as contrasted with the new, may be seen in Nos. 1046 and 1051. Indeed this distinction is observable with more or less certainty in nearly every thin section examined.

On a porphyry knob on the north side of the lake, at the corner of secs. 29, 30, 31 and 32, T. 65-6, there are, as observed in the field, transitions from the porphyry to the schist—at least to a green rock that contains the elements of the schist and nearly the same micro-structure, but yet has a petrographic alliance with the porphyry. Such intermediate rocks are found at several places, and in the field there is no line of distinction, the transition taking place in a few feet. These intermediate rocks of course have some origin. The microscope shows that the internal structures and composition are in accord with the major structures. In one direction the characters become more and more coarse and crystalline, and in the other more and more clastic, without the introduction of any new minerals. It appears as if the siliceous actinolite schist, losing locally its coarse feldspars, was converted into a dense green rock of hornblende, biotite, quartz and feldspar, in one direction, and in the other, with more or less preservation of the coarse feldspars that frequently characterize it, the same force had generated a lot of coarser quartz and secondary feldspar, and thus cemented the original debris into a granitic rock. Throughout the schist, even in its least metamorphic condition, there is a fine background of micro-granulitic quartz or of quartz and feldspar (No. 1047), which is ready, in case of the application of new forces, to take on new forms. The background matrix in the porphyry, as in the granite, is the same fine interlocked quartz, or quartz and feldspar. It is seen in the tuff in No. 1093, and in the granite in No. 1088. In the porphyry this fine matrix appears to be a micro-granulitized feldspathic debris, for numerous feldspars can be seen partially changed to such a micro-granulitized condition (No. 1093). Rock No. 1051 shows a link between the schist and the granite. It overlies green schist, and unites Nos. 1044, 1045 and 1046 to Nos. 1047–1051.

Still, under the hypothesis adopted it is not to be expected that very many actual transitions *in situ* from a plainly clastic rock to a plainly igneous one could be observed in the field. The moment a clastic rock becomes sufficiently plastic to move, under the pressure exerted upon it, it is likely to be dislodged and to enter any fissures that may exist in the firmer rocks surrounding it; and that gives it "igneous contacts" on the clastics. With these clastic rocks it would hence present not only contrasting structures, but also more or less petrographic differences. The porphyry here considered penetrates, in a few instances, the black slates associated with the green schists and with the graywackes, in the form of dikes, the slates being firm and refractory, affording most evident illustrations of intrusive action. In the area of the softer green schists, however, which are not brittle, but rather flexible, the same intrusive appears in the form of more or less round protuberances and blebs.

It is, however, with the conglomeratic condition of the sedimentaries that the most evident transitions occur to the granite. These are most evident in the field, and with the microscope the finer elements are seen to be simply compacted together, with but slight interstitial material. The crystals all being, as supposed, of the nature of volcanic ejecta, arranged somewhat by water, the elements of the rock embrace these with small amounts of erosion products, the latter increasing in amount with distance from the supposed volcanic source. One of the most evident and instructive instances of a granitized conglomerate is that seen along the south shore of the lake in sec. 31 T. 64–6. The fragmental character is most evident, and many of the pebbles are rounded. There is no short transition, but the whole rock over a wide belt acquires the granitic character. The appearance of the rock along this belt has been described as follows* by Dr. Grant:

On the northwest end of the little point in the S. W. ¼ of N. W. ¼ sec. 31, T. 65–6 (south side of the lake), there is a dark, medium grained diabase. And on the northeast corner of this point is a low outcrop of a fine grained, gray, apparently holocrystalline rock; the ground-mass is grayish and in it are small, black needles, probably of hornblende, and a few scattered, rather irregularly outlined, feldspar individuals. There are also a few rounded pebbles, up to those two inches in diameter, scattered through the rock. The specimens collected (No. 593G) show some of the pebble forms. Some of these pebbles are seen to be sub-angular, but most of them are rounded. They seem to be scattered irregularly through the rock and lie in no definite planes or layers; there is nothing in the rock to show any sedimentary lamination or bedding; it appears perfectly massive. This rock is seen in several outcrops in the N. E. ¼ of S. W. ¼ sec. 31, T. 65–6, and the shore is here usually lined with fragments of it. In the eastern part of this one-sixteenth section is quite an extensive exposure a short distance back from the shore. Here the pebbles, which have been steadily increasing in abundance eastward from the first mentioned outcrop, are very numerous. It would be almost impossible to find any surface a foot square in the rock at this place which would not contain one or more pebbles, and many areas of this size would include as

**Twentieth Annual Report*, p. 76.

many as twenty. The rock is here represented by No. 594G, and pebbles from it by No. 594aG. This rock extends along the shore in a few outcrops nearly to the east line of section 31. The pebbles grow less abundant on going east from No. 594G. No. 595G shows a more highly crystalline condition of this rock from the S. E. ¼ N. E. ¼ sec. 31. The noticeable features of this rock are its sharply outlined, rounded and sub-angular pebbles and the few scattering, white, apparently porphyritic, feldspar crystals, sometimes a quarter of an inch in length. No bedding, lamination or definite arrangement of the pebbles could be seen in the rock. It seems that this rock is a metamorphosed conglomerate, and it strongly reminds one of certain facies of the Ogishke conglomerate.

In making, subsequently, a microscopic study of this rock it was classed as a hornblendic facies of the granite,* with the following note:

What is termed the hornblendic facies of the granite is found only in a narrow strip along the south shore of Kekequabic lake in sec. 31, T. 65 N., R. 6 W. It has a fine grained gray groundmass whose constituent minerals are not readily distinguishable. In this are usually scattered small whitish subporphyritic feldspars and less evident black prisms of hornblende. This rock is different from the main mass of the granite in several respects, and the writer does not feel entirely satisfied that it is part of the granite, but it seems to be such and is placed here as a hornblende facies of the granite.

This rock (No. 595G) consists mostly of feldspar showing the usual characters, *i. e.*, much twinned with coarse and fine bands, often of tapering widths (albite and pericline), of hornblende, quartz and epidote. There is also a little biotite and magnetite. The hornblendes were at first augite, as shown by the central residua of greater absorptive power. The original feldspars were often nearly complete as crystals, but for the most part are fragments, and are clouded with fine epidote. They are cemented together by secondary deposition of fresh feldspar and of quartz. As grains they never interlock with one another.

A still more evident fragmental condition of a "porphyry," or porphyrel, is to be seen at Zeta lake, about a mile east of Kekequabic lake, where feldspar crystals as clastic elements are liberally mingled with pebbles of various kinds. There is, according to Dr. Grant, a traceable connection of this rock with the pebbly granite of the south shore of Kekequabic lake. In all respects, except in having a more evident fragmental composition, it is also a repetition of the porphyritic phase of the granite of Kekequabic lake (compare No. 1061, from Kekequabic lake with No. 1062 from Zeta lake). This porphyrel at Zeta lake has much the appearance of an igneous rock. It is in massive knobs that present a bold rounded outline quite similar to the porphyry at Kekequabic lake. It has a coarse jointage giving it a basaltic structure, and it was only after considerable field examination, and the consideration of the screened, though evident, pebbly structure that this rock was, in the field, recognized as a fragmental one. It is an obvious inference to unite this with the pebbly granite described by Dr. Grant, in a series which passes on to non-pebbly granite, and with the porphyry knobs at Kekequabic lake, which are less pebbly.

Order of generation of the new minerals. In the process of transformation from a clastic to a granite, at Kekequabic lake, the minerals appeared in the following order:

1. Actinolite, or hornblende, is formed, if it did not already exist, in the clastic rock. This was accompanied by a micro-granulation of the old feldspars, and by a

* *Annual Report*, xxi, p. 40.

similar conversion of all finer feldspathic debris into a fine interlocking background.

2. Sometimes biotite occurs at this stage, but is more likely to be abundant under powerful metamorphosing action.

3. Epidote permeates the old feldspars and gathers independently.

4. Quartz and feldspar. Sometimes one and sometimes the other is plainly earlier, but usually they were about contemporary as to date of origin.

Therefore, in conclusion, there is reason, as has been shown also in several of the annual reports, for classing this rock, from the point of view of its intrusive action and crystalline texture, with the granites, and at the same time there is much evidence, from another point of view, both structural and petrographic, for classing it amongst the clastics metamorphosed by some force which has acted at least throughout the area of Kekequabic lake.

It is also reasonable to conclude that as an intrusive rock it is derived from the clastic beds *in situ*, and had no deep-seated source. As an intrusive it was at least plastic, probably rendered so by a combination of heat and moisture, and was probably at the same time under great pressure.

The action of aqueo-igneous fusion has recently been investigated by Crosby and Fuller,* and has been recognized by numerous geologists as an efficient cause in rendering plastic and even fluid the sedimentary materials when subjected to sufficient heat, moisture and pressure. When in that state the sedimentary materials would not only be recrystallized thoroughly but would act the part of intrusives on the strata adjacent or superjacent and they would necessarily exhibit the same chemical variations, within broad extremes, as the sedimentary strata themselves. This action of the clastics under pressure is well exhibited in the limestones of the Adirondacks, which according to numerous observers have been made to intrude the adjoining quartzytes and gneisses, and to surround isolated portions of them much in the same manner as igneous rocks. This fact led Emmons and some of the early geologists to class crystalline limestone amongst the igneous rocks. But this action is mutual—isolated pieces of limestone are included in the adjoining gneiss, indicating a common history and hence a similar origin.

If this source of the granitic rocks be admitted in the case of the Kekequabic lake granites, it is likely to have been equally efficient in other localities, and indeed it rises to the importance of a general cause, applicable, in the absence of other sufficient source, to all the granites of the state. Indeed the same facts, leading to the same conclusion, are observable at other places, and especially about Snowbank lake. The Kekequabic Lake granite, however, is a small isolated area, and the transitions

*Origin of Pegmatyte. *American Geologist*, vol. xix, 1897, pp. 147-180.

and all relations are to be seen within a small compass, affording better opportunity for study. At the same time the original clastic rock is one of marked peculiarities, different from most of the clastics of the Archean, in the possession of peculiar augites and feldspars which are probably of the nature of volcanic ejecta. This peculiarity is perpetuated in the resultant granite, which is a peculiar one, different from most of the granites of the state.

(3). *Source of the characteristic elements of the alkaline magma.* If it be true that the granites and other alkaline-acid igneous rocks of the Archean are the product of the aquo-igneous fusion of the fragmentals of the Archean itself, it becomes necessary to search for the cause of their characteristic chemical composition in the nature of those fragmentals. In a previous paragraph attention was called to the essential chemical differences between the alkaline magma and the ferro-magnesian. They consist in the presence, in the alkaline, of a noteworthy per cent of the alkalies, and of a large per cent of silica, a fact which precludes the derivation of the alkaline magma from the ferro-magnesian by any process of lixiviation, or "fermentation," or differentiation. It seems to be required, therefore, to find a satisfactory explanation of the existence in the fragmentals of the additional elements in excess of those amounts of the same which occur in the ferro-magnesian magma.

The nature and origin of those fragmentals immediately come into consideration. They are largely of volcanic origin, and contained originally not only the augite crystals from which has been derived their predominant hornblende, but also the olivine, the menaccanite and the soda-lime feldspars which characterize the ferro-magnesian rocks of the Kawishiwin. These original minerals were subjected to the manifold disintergration and final destruction which is incidental to oceanic action. Their soluble parts went into the oceanic waters, and their insoluble constituted the debris which went, so far as it was able, to form the sedimentary strata of the Archean. The ocean's waters must have been frequently heated by volcanic ejections, and locally charged with the gases and acids which characterize volcanic products. Such ejections would give rise to soluble chlorides and sulphates of the alkaline bases and of iron and would thus be able to take up silica from the decay of the rocks, and these substances would be distributed by currents to all parts of the globe. These salts would vary from time to time, and from place to place, sometimes reaching saturation. Precipitation would take place when the balance of their saturation point was broken by physical changes, such as lowering of temperature or an influx of currents bearing elements that caused a change in their chemical combinations. All these physical irregularities must have been due, in this early volcanic age, primarily to the movements set on foot by volcanic activity. It is impossible to state, and even to conceive, of the millions of fluctuating conditions in that primeval ocean, tending to work over the volcanic ejectamenta and the prior-formed ferro-magnesian crust. The essential inquiry, in this search, is to ascertain whether there was any source for potash and for an excess of silica, such that these could accumulate in the fragmentals in greater proportions than in the earlier rocks.

At ordinary temperatures, and under ordinary conditions, silica is quite insoluble, but in an alkaline water it is soluble and is carried from one place to another in the crust of the earth, in large amounts. In a heated alkaline water larger amounts may be held in solution. As it is known that throughout the Archean fragmental rocks there is a very large amount of microscopic silica, sometimes constituting important beds due to oceanic precipitation, as in the jaspilytes and other flinty deposits, the inference is natural that the ocean was in suitable chemical condition to hold in solution very large amounts of silica, and therefore that it must have been alkaline and probably heated.*

Such alkaline quality, residing in the ocean, could not have been derived, so far as it consisted of potassium, from the pre-existing rocks, for, as already shown, they contained no potassium. It must therefore have been resident in the ocean, from which it was precipitated, like the silica, and took its place, in form of such chemical combinations as its environment allowed, amongst the other sediments. Its ultimate origin might be further considered, but at this point it is necessary simply to call attention to the nature of the precipitate which would result from an alkaline ocean in which were numerous active volcanoes.

The acid exhalations of volcanoes are well known. They are sulphuric and hydrochloric acid, and also carbonic. But as the last may not have existed in the acid products of the Archean volcanoes, it may be omitted from this inquiry. These acids, mingling with the oceanic waters, would seize on the alkaline bases, liberating the silica. The soluble salts thus formed would be disseminated in the ocean, and it would result that the alkalinity would be locally intensified. In general, however, in case of the disturbance of the chemical equilibrium, there must have been a precipitation of silica and of an alkaline silicate, and even without any disturbance from the addition of volcanic acids, the ocean may have given everywhere a slow accumulation of such silicates. Owing to the avidity with which potassium seizes on oxygen, and the insolubility of the potash feldspars, it is apparent that the silicates of the alkaline feldspars would be immediately and perhaps copiously precipitated. This seems at least to have been the case. The Archean ocean, therefore, was unfit for animal life, and was characterized by the prevalence of the lightest of the alkaline bases (potassium) in some such way as, later, the Silurian was charged with lime and magnesia, and, as the present, with soda. It resulted that the world's great stock of

*On the precipitation of silica from solution in the Archean ocean the reader may consult—"On a possible chemical origin of the iron ores of the Keewatin in Minnesota." N. H. and H. V. WINCHELL. *American Geologist*, vol. iv, p. 291, 1889.

potassium was stored up in the Archean sedimentary rocks, in the form of alkaline silicates, where it remains to the present.

The oldest quartz-porphyry. This oceanic source may be applied to the earliest quartz-porphyry. Not enough examination has been given to this quartz-porphyry to warrant positive conclusions as to its source, but a few facts may be recalled here which seem to be in consonance with this idea.

The oldest quartz-porphyry known is that which is in the Lower Keewatin, forming a large mass southwestwardly from Snowbank lake. It is described in general terms in the twenty-fourth annual report (page 69). The following leading facts may be mentioned:

1. It lies between two greenstones, the older one being the massive portion of the Kawishiwin and the later one the fragmental portion, and is perhaps 2,000 feet across.

2. Between it and the older, however, is a curious conglomerate, made up entirely of greenstone debris, but with a few fragments of jaspilyte.

3. It does not cut, so far as seen, the older greenstone, and at no place has any quartz-porphyry been known to cut a greenstone of that date.

4. It has supplied many large fragments to the later greenstone, and its finer debris is scattered abundantly through the same (plate Z, vol. iv).

5. This quartz-porphyry varies. It does not generally show any sedimentary structure, but occasionally it presents characters that are usually accredited to oceanic origin. For instance, it becomes roughly schistose, in places, and ridged with interrupted finer belts resembling siliceous argillyte. It holds pieces of greenstone and of slaty greenstone, varying in size from ten inches (rounded) downward to half an inch, also pieces of jaspilyte and rounded quartz. The slaty greenstone is like argillyte and runs usually with the structure, standing on edge. The rock contains much quartz in grains usually less than a pea in size, but also as large as an inch in diameter, the last being very rare, while other quartzes as if phenocrysts of quartz-porphyry, are abundantly disseminated.

6. In some places the bulk of the whole rock consists of more or less rounded fragments of orthoclase and quartz lying in a pellucid matrix which appears to be essentially quartz of a kind like the so-called chalcedonic quartz seen in the jaspilyte, mingled with equally fine feldspar.

7. This mass of quartz-porphyry occupies about the position of the great jaspilyte lodes, *i. e.*, it is subsequent to the massive greenstone of the Kawishiwin.

It may be inferred, from the fact that it succeeds immediately after the greenstone conglomerate lying on the agglomerated condition of the Kawishiwin, that, if it resulted from oceanic precipitation, it was formed at a time when the ocean was greatly agitated, and hence that chemical precipitations would have been profuse, such agitation probably being caused by local volcanic action.

If we allow the chemical precipitation of the silica of the jaspilyte in the midst of the greenstone Archean, or closely following the congealation of the earliest greenstone crust of the earth, thus producing the jaspilyte masses which everywhere occur in the greenstone, it is reasonable to presume that those conditions may have been prolonged in time and intensified in degree as well as extended in area, and that under favorable circumstances an enormous amount of siliceous mud, varying occasionally to pure silica, may have been produced. There have been noted repeated instances of the gradual passage, by inter-stratification, from jaspilyte to argillyte, and to a chloritic schist, as well as to iron ore. In one remarkable instance such banded jaspilyte has been seen to be at the same time a coarse conglomerate, showing that violent agitation as well as chemical precipitation was an attendant of the Archean ocean, both taking place, in some cases at least, at the same point and simultaneously.

Under conditions producing chemical precipitation of silica, if the Archean ocean was deep, and if the precipitation was rapid and abundant and the mass cooled slowly (for the Archean ocean at this time must be considered to have been heated), it might be that crystals of quartz of considerable size would be formed throughout the mass, and that all the quartzes of this porphyry may thus have originated, in some such manner as selenite, pyrite and other crystals form in a mud that holds the elements of those minerals in saturated solution. The general absence of a banded stratification, under this hypothesis, is the greatest obstacle; but if the precipitate accumulated rapidly, it must have been subject to the same forces, whatever they were, which excluded the banded structure from great thicknesses of fragmental greenstone, and from greater thicknesses of the Ogishke conglomerate, and from the Stuntz conglomerate. It is perhaps due to copious and quick accumulation that the sedimentary structure is not seen in some large and important fragmental terranes. A subsequent crystallization of the mass would also result in the obscuration, or the obliteration of the sedimentary structure, a fact seen in many great limestone strata of the Silurian.

If, however, as seems to be proved by the presence of orthoclase crystals in this porphyry, the precipitate was not wholly of silica, but included a considerable amount of potassa, the crystallization of such a deposit of alkaline mud would not only rearrange the molecular structure of the deposit throughout its whole thickness, but would still more effectually destroy whatever sedimentary structure the ocean may have stamped upon it. Elsewhere it has been shown by the writer that potassium was probably retained as an element of the atmosphere, after the solidification of the first crust, for a period long enough for the cooling of the crust and for the ocean to bring potassium within the bounds of possible condensation and precipitation.* This was an inference from the observed later introduction of acid-alkaline rocks in the Archean than the ferro-magnesian. It is a striking coincidence with that argument that, here, the oldest known acid rock not only shows signs of oceanic agency, but also embraces, along with phenocrysts of quartz, those of orthoclase, and that the fine matrix of these phenocrysts is both siliceous and alkaline, in a state of fine crystallization.

The heated waters of the Archean ocean had, at the date of this precipitation, been able to accumulate only a coarse "mud-conglomerate," a stratum seen at this place to have a thickness of about 105 feet, made up wholly of roundish and more or less squeezed greenish pebbles. This band sometimes has been designated a "greenstone conglomerate" from the nature of its pebbles, but in other cases it has been styled "mud conglomerate," from the fineness of their grain and the smoothness of their outlines, which also indicates an original plasticity. Under such conditions not only would the alkaline ocean hold in solution much silica, but such silica would, with alumina (also present as a product of decay and dissolution of the greenstone crust), necessarily unite to form such minerals as orthoclase. Hence would result, posssibly, from a supersaturated solution, a rock as an oceanic product which is usually considered a normal igneous rock resulting from fusion.

Even with this origin for the earliest acid rock, which is here a quartz-porphyry, this rock is not far removed from the same operations and the same agencies as those which are called igneous, for heat and moisture and plasticity are the essential conditions for the production of all acid igneous rocks, unless they be derived from some primordial magma. This explanation differs only in requiring a lower degree of heat (less than the boiling point of water), a longer period for crystallization and an enormous scale of operation, as contrasted with the restricted limits of normal volcanic action. It also implies the formation of the rock over broad expanses of the ocean's bed rather than in the reservoirs of the earth's crust; and as a corollary it points to the porphyritic rather than the granitic as the structure assumed by the earliest acid rocks.

Whence the Archean ocean obtained this large supply of potassium, it is not necessary to inquire. Whether it was imprisoned at greater depths within the earth, and for that reason did not appear in the ferro-magnesian earliest crust, but was thrown out by later volcanic action, and thus reached the sea, or was retained still in the atmosphere and was precipitated first into the ocean and later was thrown down as alkaline silicates as above indicated, is subject for legitimate further speculation, but it is not within the scope of this discussion. It might be added, however,

*The origin of the Archean igneous rocks. *American Geologist*, xxii, 299, 1898.

that there are weighty considerations, based on the chemical characteristics of potassium, its comparative specific gravity and its avidity for oxygen, that tend to indicate that potassium remained in the earth's atmosphere not only longer than the other alkalies or alkaline earths, but also during that long heated condition of the earliest crust occupied by the slow congealing, and finally the cooling of the first formed film before it was possible for the ocean to rest upon it.

The view above presented of the origin of the igneous rocks, especially those of the Archean, is essentially the same as that adopted by Hutton (1785), Keferstein (1834), Herschell (1836), Hunt (1858), Le Conte (1872), Dutton (1880) and numerous other geologists. But these geologists labored under the wrong idea that the oldest rock was essentially granitic, and much of their reasoning was vitiated by an attempt to explain the rock succession from the alkaline to the ferro-magnesian instead of the reverse.

THE TACONIC.

The detrital rock formations included under this term in Minnesota are separated from the Archean by a profound break in the stratification, as well as by difference in crystalline condition. They are divided between Animikie and Keweenawan, and are supposed to be the representative of the Lower and Middle Cambrian.

The base of the Taconic. The conglomerate which occurs at the base of the formation has been examined at various places in Minnesota, viz., at the south side of the Giant's range (No. 372H), S. W. ¼ N. W. ¼ sec. 32, T. 60–13, where it lies upon the granite of the Giant's range and embraces much debris from the granite. It is exposed to the depth of twelve or fifteen feet. At the top it contains considerable green uncrystallized material, with large feldspar fragments, and has an indistinct gneissic structure which seems to lie nearly horizontal, with a schistosity running northeast and southwest. At the top are some pebbles of quartz and green rock, some of them two inches long. In the field this conglomerate seems to grade into the granite.* A diamond drill section was made in N. W. ¼ S. W. ¼ sec. 27, T. 60–13, passing from black slates through quartzyte, ore, quartzyte, and conglomerate, into the Giant's range granite, the whole depth being 323 feet. The base of the Animikie here contained not only feldspars from the granite, and lavender-blue quartz grains from the same source, but also much green debris from the adjoining and underlying Keewatin. The coarsely conglomeratic portion of the Animikie here was only three or four feet in thickness. In some other drill sections the conglomerate was also quite thin, and in some instances the basal quartzyte was found to lie directly upon the granite with no apparent conglomerate. A thin conglomeratic

*Owing to the fact that the supposed Animikie is immediately in contact with granite on S. E. ¼ N. E. ¼ sec. 35, T. 61-12, and shows no conglomerate, as well as on account of the nature of the ore and of the conglomerate itself at the above locality, there is some uncertainty as to the Animikie age of the conglomerate. The granite may here be intrusive into the Upper Keewatin, and into the Lower Keewatin at other points in the vicinty. See *Seventeenth Report*, pp. 86, 94.

phase occurs at the bottom of the Animikie further west, in the region where the chief economic development of iron ore has taken place,* and at the falls of Prairie river.

Pokegama quartzyte. The basal conglomerate of the Animikie soon graduates upward into quartzyte which is well developed at Pokegama falls on the Mississippi river, causing the falls. From its favorable and conspicuous exposure at this place it has been named Pokegama quartzyte. The thickness of this quartzyte is not known to exceed fifty feet, and it is sometimes less than twenty-five. It varies from an ordinary quartzyte whose rounded grains are cemented by secondary silica into an interlocking firm plexus of quartz, to a very fine-grained one which approaches flint in its texture. The finer portions prevail toward the east, and at Gunflint lake a genuine flint is seen interstratified near the bottom of the Animikie. This flinty character is quite prominent at the base of the Animikie still further northeast, but as a quartzyte this member is lacking at Gunflint lake. There is, however, at Gunflint lake, some fragmental quartz in the bottom of the iron-bearing member.

The iron-bearing member exhibits a somewhat irregular manner of succession after the quartzyte, and sometimes has an alternation with it in subordinate strata. In such case the quartzyte is very fine grained, and grades into the quartzyte which runs through the iron-bearing member, becoming crypto-crystalline and non-fragmental. The ore is sparsely disseminated in isolated grains throughout these alternating bands.† In the same manner the upper limit of the iron-bearing member is rather indefinite. The thickness of the iron-bearing member is several hundred feet, and sometimes reaches nearly 1,000 feet. The ore is usually hematite on the western Mesabi range and magnetite on the eastern. The original nature of the iron-bearing member is believed to have been a glauconitic sandrock, but at the present time it consists almost wholly of silica and hematite, in secondary condition constituting the iron ores of the Mesabi iron range. The alteration of the original glauconite is not entirely completed. Hence, by the examination of an extended series of specimens, the steps of the alteration, its causes and its final products, can be traced.‡ The great economic importance of this member of the Animikie has warranted a more extended presentation in a special chapter on the iron ores of the state (vol. iv).

Limestone occurs just above the iron-bearing member. It is impure and usually dark colored, and can with difficulty be distinguished from the overlying black slates. It is but few feet in thickness. It extends, apparently, the whole length of the Mesabi range, but has been identified in place only at the extreme ends, viz.: sec. 7.

*J. E. SPURR. *Bulletin x*, p. 5.
†J. E. SPURR. *Bulletin x*, p. 229.
‡In *Bulletin x* of the survey this subject has been fully discussed and illustrated by J. E. SPURR.

T. 58-17, and doubtfully on the shores of Gunflint lake. Boulder masses have been found, however, at one or two intermediate points, which are supposed to have been derived from this stratum. The thickness of this limestone does not probably exceed twenty feet, varying from place to place. It is essentially only the bottom phase of the black slates. It exhibits a fragmental structure, except when it has been subjected to the alteration incident to the formation of the iron ore deposits.

The upper or slaty member, with its siliceous variations, constitutes the bulk of the Animikie, and is probably several thousand feet in thickness. It has been more fully studied in the region of Gunflint lake, where it presents abundant outcrops in the perpendicular cliffs facing toward the north. Dr. Grant has there divided it into two parts: the lower part is composed largely of black slates, often very fissile and apparently carbonaceous, the lower portion being flinty, having a total thickness of 1,050 feet, of which about 100 feet represent the diabase sills; the upper part, or graywacke slate member, more firm, often a quartzyte, having a total thickness of 1,900 feet, of which about 250 feet are composed of diabase sills.

The Grand Portage graywacke. In the Indian Reservation at Grand Portage is a more fragile member of the Animikie. It outcrops at various places on the Grand Portage trail, especially toward the western end of the trail. This rock is greenish, gritty, rough and unevenly bedded, having a coarse conchoidal manner of disintegrating under frost and sun. It has suffered great denudation. It probably once rose to the summits of the great dikes that form prominent hill ranges crossing the country, but has been removed, leaving those dikes standing with sheer walls rising from 50 feet to 150 feet above the talus. This graywacke is supposed to overlie the quartzyte and slate of the black slate member, but its extent and stratigraphic position have not been satisfactorily established.

The summit of the Animikie has never been seen so as to be identified. Whether the fragmentals of the uppermost, graywacke member, probably represented by the Grand Portage graywacke, gave place suddenly to the next higher fragmental stratum, which is the Puckwunge conglomerate, the fragmental base of the Keweenawan, is not known. But as there was a period of great disturbance which witnessed the upheaval and the profound metamorphism, as well as the fusion of the Animikie before the accumulation of that conglomerate, it is reasonable to suppose that there were other rocks formed before the commencement of the conglomerate. The facts that are mentioned in the chapters devoted to the Duluth and the Pigeon River plates, and referred to in connection with the Lake County plate, show that there was more or less of eruptive activity prior to that conglomerate, and hence that there were probably agitated seas and coarse rapid detrital accumulation. These significant facts are as follows: (1) An amygdaloidal (?) trap (No. 1847) lies on the Animikie at the most southerly of the Lucille islands. This is supposed to be near the top of the Animikie. (2) The record of the deep well drilled at the Short Line park, near Duluth, shows a series of trap layers resembling those seen at Duluth below the quartzose conglomerate exposed in the St. Louis valley near Fond du Lac. This conglomerate is supposed to be the western representative of the Puckwunge conglomerate. (3) In the vicinity of Beaver bay, where the Beaver Bay diabase is charged with masses of feldspar rock, there is seen to be a loose red conglomerate and a diabase basalt below the Beaver Bay diabase. If there be equivalence of date between the Beaver Bay diabase and the parent mass of gabbro, as supposed, then there must have been at least one and perhaps several surface lava flows anterior to the outbreak of the gabbro revolution. This superposition is seen at the bite of the little bay (Two Harbor bay of the annual reports) sec. 12, T. 54–9, where the lower portion of the great diabase is a pudding-stone of feldspar masses. All this evidence, however, is still inconclusive and the nature of the top of the Animikie remains an unknown quantity. It may have blended gradually with volcanic ash and occasional lava sheets, but was terminated by the great revolution which gave origin to the gabbro and the red rock. The first recognizable and fixed datum, in the form of a clastic stratum, after the Animikie, is the Puckwunge conglomerate, and that is also posterior to at least some of the great dikes of Grand Portage, to the red rock and to the great gabbro mass.

The age of the Animikie is considered to be that of the Lower Cambian. It may be below the horizon of Olenellus, which sometimes restricts the downward extension of the Lower Cambrian, but as it is followed above by the sandstones which graduate upward into the Upper Cambrian, as seen on the south side of lake Superior, and in the valley of the St. Croix, it is at least in the proper place for the Lower Cambrian. According to the conclusion reached by Mr. Spurr that the iron ore of the Mesabi is derived from a glauconitic sandstone, there is reason to presume that large quantities of foraminiferal organisms once lived in the Animikie ocean. In the St. John group of New Brunswick, Mr. W. D. Matthew has shown* the existence of foraminiferal forms associated with noticeable amounts of iron ore. In the Animikie in the Thunder Bay region, Mr. G. F. Matthew has also described a Taonurus-like impression which he has named Medusichnites.† The Canadian geologists uniformly refer the Animikie of the Thunder Bay region to the Lower Cambrian.

Perhaps the strongest indication of the non-Archean age of the Animikie lies in the non-conformity at its base. All earlier strata are highly tilted, and usually nearly to verticality. The Animikie is rarely tilted as much as forty-five degrees from horizontality, and over large areas it is nearly level, lying on the vertical strata

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* *Trans. N. Y. Acad. Sci.*, vol. xii, pp. 108–120, 1893.

† *Trans. Roy. Soc., Canada*, vol. viii, Sec. iv, p. 143, 1890.

of the Keewatin, this being its position also in Ontario. Such a break in stratigraphy implies a long epoch during which the folding of the Archean was produced. There is no geological horizon between the Upper Cambrian and the Archean which seems commensurate with these features except that which is usually put at the base of the Lower Cambrian.

Extent of the Animikie. Entering the state from the northeast at Pigeon point, this formation runs westwardly along the international boundary to the vicinity of Gunflint lake where it strikes into the state, to the vicinity of Chub (Akeley) lake where it disappears. The manner of disappearance is interesting and suggestive. It seems to separate into two parts for a short distance, one part leading into and under the gabbro which penetrates it in the form of dikes and sills finally overwhelming it, and the other running a few miles in an interrupted manner in a spur-like prolongation further north. This spur-like northern prolongation is last seen (No. 1896) near the working of the Gunflint Lake Iron company's exploration, S. W. ¼ sec. 21, T. 65-4 W., at half a mile north from the gabbro mass, separated from the gabbro mass by an intervening belt of Keewatin greenstone belonging to the great greenstone area of the region. It is known also to run eastward and to be the cause of several iron locations. The southern edge of the exposure, in S. W. ¼ sec. 21, shows a high dip north, and, indeed, it is vertical in many places along the southern borders of the mass. Then it bends, at lower levels, so as to be flat, and at favorable points of view it can be seen to change from a vertical or northward dip to a southward dip, there being a continuous swing between a southerly dip of 10° to 20° (extreme) through horizontality to verticality. The flexure is abrupt and on the southern side of the hill, the horizontal and southward dip being on the northern slopes. The appearance, where the mass stands vertical, is very much like some black jaspery outcrops in the Keewatin. The manner of superposition or contact on the greenstone at this point cannot be seen. While this northern spur has been considered a part of the Animikie, there are certain anomalous facts of position, structure and petrography which, not having been seen elsewhere in connection with undoubted Animikie, lead to the hypothesis that this part of the northern spur is a ferruginous belt belonging to the Keewatin, and that the real strike of the Animikie is along the southern spur mentioned, lost in the gabbro.

A series of similar ferruginous outcrops occurring southwestward further, beginning with and including the "mine" of the Gunflint Lake Iron company at the centre of sec. 28, T. 65-4 W., and extending along the stream westward from Akeley (Chub) lake to Gabimichigama lake, Fraser lake, Thomas lake and Birch lake, as far as to the appearance of undoubted Animikie in secs. 27 and 32, T. 60-13 W., fall into this uncertain category, with probability of Keewatin age for all of them. These ores are intimately associated with the large amounts of the rock muscovadyte which is not known to occur in connection with the Animikie and its ores, but which, in several places, has been observed to be derived from the Keewatin by metamorphism. Therefore, it appears that the Animikie is lost under and in the gabbro at a short distance from Gunflint lake, and reappears, with its own characters, only affected by contact metamorphism, on the west of the west side of the gabbro southwestward from Birch lake, and thence continues along the south side of the Giant's range, constituting the Mesabi Iron range* to Pokegama falls. Its extension south of the belt of iron mines, on the western Mesabi range, is unknown, owing to the heavy mantle of drift, but it is well known that the black slates of the Animikie overlie the iron ore horizon all along the mining belt.

What becomes of the Animikie, after its disappearance in and under the gabbro, has been one of the interesting geological problems of the survey. From preliminary field examinations it was stated by the writer, twenty years ago (1878), that the sedimentary rocks at various places along the shore of lake Superior, and notably on Pigeon point, at the Great Palisades and at Beaver bay, had been converted into crystalline rocks, and had been fused by contact with the basic igneous rocks. Nearly every year from that time to this has contributed in the progress of the survey to the verification and the extension of that truth. It has already been applied in the discussion of the Archean and its igneous rocks. In the Taconic are some of the most evident facts and the most convincing transformations tending to this result. They are recorded in some of the annual reports and in occasional papers, and are systematically summarized where they occur in some of the special chapters of this report. Therefore, at this place, in tracing out the extension of the Animikie, it may be assumed that, in general, the strike of the red rock shows the strike of the Animikie. But as there is reason to assume that the mass of the gabbro moved superficially toward the south, it is necessary to allow that the fused products of its intrusion partook in that movement. Indeed, it is certain that, in several instances, the red rock formed lava flows which reached the latitude of the present shore line of lake Superior; and toward the western limit of the gabbro where it seems to have flowed farther as a great mass than toward the east, so the red rock is further displaced from the locus of its origin. It is not known that this red rock flow has no interruptions in surface extension from Lake county westward to Duluth, but it is highly probable that, with occasional variations and mutual overlapping with the cotemporary diabasic flows from the gabbro, its general continuity could be seen if the forest and the drift could be removed. It is seen at many places, as at Baptism

*It is the opinion of Dr. Grant that the Animikie continues, under disguised conditions, as formerly supposed, and as represented in the annual reports and in some of the chapters devoted to the Mesabi Iron range, all along the northern border of the gabbro. Facts mentioned by him in the chapter on the Akeley Lake plate are indicative of the Animikie age of the iron at Akeley lake, and that locality might be excepted from the hypothesis above expressed.

river and at Beaver bay, to be confusedly interlarded with and cut by basic trap, and also to appear as if intrusive in the gabbro and in the Beaver Bay diabase. Its physical relations to the gabbro and to the Keweenawan will be given in treating of the igneous rocks of the Taconic.

At the same time that the northern strike of the Animikie is westward along the south side of the Giant's range, there are points further south where it has been doubtfully identified. There are certain hardened and metamorphic rocks at Duluth which have been referred to the Animikie (Nos. 807, 1966), and the slates which appear at Thomson, and especially at the cuts by the Northern Pacific railroad southeast from Carlton, appear to belong to the Animikie. What may be the direction of strike and dip, and what the irregularities which the Animikie suffers in order to appear at these places, dipping southerly, while along the Giant's range fifty miles further north it also dips southerly, can only be conjectured. In this interval is the St. Louis valley, where not an outcrop occurs, and which is deeply buried under drift and perhaps under the Cretaceous. By reference to the chapter devoted to Carlton county (plate 56) it will be seen that only a portion of the rocks usually known as the Thomson slates are included in the Animikie, the rest being of the Keewatin.

Metamorphism of the Animikie. In St. Louis county, southwestward from Birch lake, in the angle between the granite of the Giant's range on the north and the northern line of the gabbro on the south, the Animikie appears in the form of a very fine-grained biotite mica schist with cordierite (Nos. 1708, 370H). The outcrops are not numerous, and it is impossible to define the limits of this metamorphism. The iron ore of the Animikie at the same place is converted to magnetite, accompanied by the generation of more or less actinolite and cummingtonite.

The mica schist at Little Falls, on the Mississippi, in Morrison county, also has some characters that suggest its Animikie age, viz.: its fine grain, its distinct sedimentary structure and its low angle of dip. There is also at Little Falls a massive igneous rock resembling gabbro (No. 1678), which increases the parallelism with the Animikie. At Little Falls the schist is garnetiferous and staurolitic, and at Pike Rapids embraces a bed of limestone (No. 1681).

The Puckwunge conglomerate. If the Animikie be separated from the Keweenawan on the basis of its fragmental rocks, this conglomerate would be the bottom of the Keweenawan; but if the earlier igneous rocks (compare the chapter on the Duluth plate, vol. iv) be included in the Keweenawan, that term will embrace an unknown interval of time and probably some of the latest clastics of the Animikie. This conglomerate expresses a profound and extensive non-conformity and erosion interval. It contains not only pebbles of quartz-porphyry and other forms of the red rock, but much debris from the Animikie slates, including the peculiar rock taconyte from the iron-bearing member of the Animikie (Nos. 852B and 852C). It is first seen in Minnesota in the valley of the Puckwunge, a small stream entering Pigeon river about a mile south of South Fowl lake (Nos. 1903 and 2069). The thickness here exposed, including the associated grit, amounts to 144 feet, with probability of as much more below the visible portion.

The dip is toward the S. W. by S. 12°, and is distinct. The rock is essentially a white quartz pebbly conglomerate, the coarsest stones being about six inches in diameter, rounded-lenticular and hard, altogether water-worn. There is very rarely a distinct banded red-jasper pebble, and some that are not banded, and more common a gray, siliceous pebble like basanyte. Some of the pebbles are reddish brown. The great majority of them are of vein quartz, but some appear of chalcedonic fineness of grain. The general character and appearance of the mass are like those of the quartz-pebble conglomerate seen in the St. Louis valley, a short distance above Fond du Lac.

In collecting pebbles (No. 2069) a special effort was made to obtain some that might prove to be characteristic of some earlier formation, and among these the rock taconyte was sought for. Thin sections made from some of these showed that the rock from which they were derived was of clastic structure, though now composed of secondary silica and hematite and identified with the taconyte of the Animikie, thus fixing the conglomerate later than the Animikie. One of the most common sorts of pebble is that of a gray, granular quartzyte, which is easily referable to the slaty quartzyte of the upper part of the Animikie.*

This conglomerate is known again at one mile southwest from Grand Portage village. described by Mr. Elftman as follows: It is in a high bluff facing the lake, appearing white as viewed with a glass from Grand Portage island. The rock making up this bluff is coarse, white quartzyte, becoming conglomeratic in places. Thin pebbles of slate are scattered throughout the rock. It is apparent that only the upper part of the formation is exposed here. Quite a distance intervenes between the conglomerate and the siliceous member of the Animikie, in which there are no outcrops. The exposed thickness is about 100 feet. The stratification of the sandstone is very plain. There is a diabase flow twenty feet thick, superposed on the conglomeratic quartzyte, fine grained and compact in its lower portion, and amygdaloidal in its upper. Small portions of the quartzyte are included in the diabase, which resembles that found on Grand Portage island. Above this diabase is a stratum of quartzyte varying from a few inches to two feet in thickness; and above this are successive layers of diabase with more or less of detrital matter between them. The successive layers of diabase, and all the quartzyte, are cut by a dike of diabase about vertical, running east and west, about ten feet in width. The general strike of the conglomerate seems to connect it with that seen in the Puckwunge valley and at Grand Portage island. The distinctions between the Animikie siliceous slate and the conglomerate or quartzyte are as follows:

Animikie quartzyte. Slaty, dull or earthy appearance, very fine grained, cut by Keweenawan dikes; also by post-Keweenawan dikes.

The *Keweenawan conglomerate* contains flat pebbles of the Animikie slate and quartzyte. It is usually fresh and bright in appearance. It is cut only by the later dikes. On Grand Portage island it also contains red rock pebbles.

The structural conditions are expressed by the following diagram (figure 1), drawn by Mr. Elftman. In this diagram the supposed place of the Grand Portage graywacke is in the interval of "no outcrop."

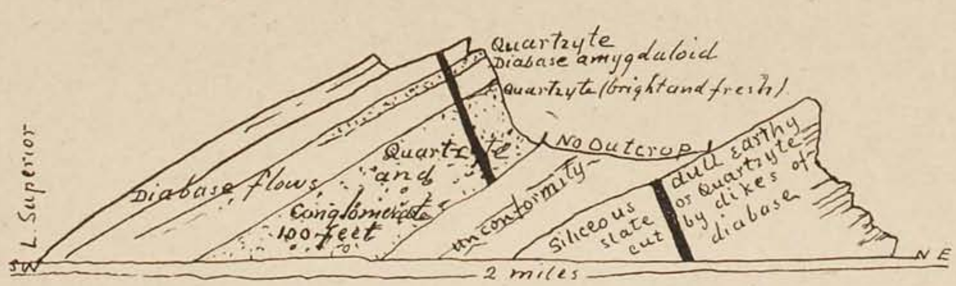

FIG. 1. CROSS SECTION AT GRAND PORTAGE.

The first point in the region of Grand Portage at which this conglomerate was observed was on Grand Portage island (No. 254), where it shows about twenty feet of

*Compare *Twenty-fourth Annual Report*, pp. 34-39, for the details of the stratigraphic relations of this conglomerate in the Puckwunge valley.

stratification, is cut by a dike nine feet wide and is covered with a surface diabase flow or a succession of flows. It here embraces distinctly quartz-porphyry and debris from the hardened clastics of the Animikie. The Animikie was therefore upturned by eruptive disturbance and the whole series of red rocks which appear as a result of fusion of the Animikie on the east flanks of mount Josephine and at the head of Wauswaugoning bay, and on Pigeon point, had been produced prior to the date of this conglomerate.*

From the region of Grand Portage this conglomerate extends eastward under the surface of lake Superior, reappearing at the southwestern end of Isle Royale, where it is coarse and quartzose, and where it is in like manner overlain first by some trap sheets (No. 562) and then by a hard sandstone.

Toward the southwest it is believed to be at first less developed. Its upper parts are apparently replaced by sandstones having a red color or by red laumontitic conglomerates. As such it appears a short distance up the Baptism river, while along the shore further east as far as to Little Marais and Manitou river are several conglomeratic bluffs at the lake shore, which are probably representatives of the same general horizon, separated by lava sheets and modified by an abundant supply of igneous basic debris.

The next that is known of it is in the valley of the St. Louis river, where it affords conspicuous exposures, as described and illustrated in the chapter devoted to Carlton county, and, according to the record of the deep well at Short Line park (Duluth plate), is separated from the Thomson slates by a series of igneous rocks having a thickness of ninety-one feet, although along the river it lies on those slates.

At New Ulm, but on the north side of the Minnesota river, is an unequivocal outcrop of the same conglomerate. It here lies on red granite, probably of the age of the red granite, or red rock, of the gabbro age, and its pebbles are coarse and varied, some of them being of the peculiar jasper called taconyte (Nos. 852B, 852C), a striking and unmistakable index of parallelism with the Puckwunge conglomerate of the northeastern part of the state.† It here lies below a large quartzyte formation which is well known, both in Minnesota and Wisconsin, in the latter state having been called Baraboo quartzyte, while it received from Dr. C. A. White, of the early Iowa survey, the name Sioux quartzyte.

In addition to these localities, Sweet has described it in T. 32-6 W., Wisconsin,

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*The reader is referred for a consecutive discussion of this interesting distinction to the following literature:
Tenth Annual Report, Minnesota Survey (for 1879) [1882] pp. 45, 46. Description of the rock section

Copper-Bearing Rocks of lake Superior. *Mon. v, U. S. Geological Survey*, 1883, pp. 297, 367, 405, and figure 16 on p. 297. The conglomerate is referred to the Animikie by Irving.

Note on the Keweenawan Rocks of Grand Portage island, north coast of lake Superior. *American Geologist*, xiii, p. 437. Grant here shows that the conglomerate belongs in the Keweenawan, probably near the bottom.

The anorthosytes of the Minnesota shore of lake Superior, *Bulletin viii*, Minnesota Survey; and The Norian of the Northwest, an introduction to the last. Here is emphasized the necessity of separating the gabbro from the rest of the Keweenawan, thus dividing the Keweenawan, as defined by Irving, into two parts.

The eruptive and sedimentary rocks of Pigeon Point, Minnesota. *Bulletin cix. U. S. Geol. Survey*, 1893. Bayley here shows that the quartz-porphyry and red rock are formed by fusion of the Animikie by the gabbro.

†A rational view of the Keweenawan. N. H. WINCHELL. *American Geologist*, vol. xvi, p. 150.

on the Chippewa river. Here it underlies a massive quartzyte, and reaches the thickness of 300 feet.* It has been fully described by the Wisconsin Geological survey.† It is probably the same as that described by Van Hise at the west of Agogebic lake, where it contains rolled pebbles of quartz-porphyry and certain phases of basic eruptives and debris from the Archean. ‡

The later Keweenawan fragmental rocks were at first interstratified with sheets of lava of diabasic nature. They are frequently conglomeratic, but consist largely of debris from the cotemporary trap. These beds of loose, fine, red conglomerate or of sandstone, are apt to be thickly sprinkled with crumbling laumontite, an additional circumstance which increases their friability. Hence, they are frequently seen along the lake shore, as at the mouth of Manitou river, and west from Little Marais, forming perpendicular cliffs capped with the next overlying lava sheet. Such conglomerate is to be seen in the St. Louis valley, above Fond du Lac, interstratified with red sandstone and red shale, these beds in the aggregate reaching a thickness of over 800 feet. Here no known trap-sheets are interbedded. However, in the record of the deep well at Short Line park, a series of trap flows separates the red sandstones and conglomerates from the basal, coarse Puckwunge conglomerate, reaching a thickness of 217 feet. The whole formation dips, at and above Fond du Lac, at an average angle of about six degrees toward the south-southeast. The uppermost layers become more siliceous and serve as a good building stone.

As the eruptive forces died out the sandstone became still purer, and indeed quite pure, forming first the Hinckley sandstone, quarried in the gorge of Kettle river in Pine county, and later the sandstones of the St. Croix valley, which are fossiliferous and alternate with magnesian shales and magnesian limestones, thus introducing gently the fauna of the Upper Cambrian.

During this later part of the Keweenawan in the northwest, both during the continuance of gentle or local eruption, and after its entire cessation, the whole region was undergoing a slow settling, bringing the oceanic waters over more extended areas of land,§ and burying under the later sandstones, not only the old Archean rocks, as seen in Carlton county (vol. iv, p. 16), but also concealing from sight the older beds of the Keweenawan itself, as exhibited at Taylor's Falls. It thus appears that the Manitou portion of the Keweenawan eruptive rocks are interjected in the midst of a period of sandstone accumulation. They would thus be expected to occur somewhat locally and at irregular intervals, and about the peripheries of the eruptive centre they would be found to diminish gradually as to thickness and to

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* Notes on the *Geology of Wisconsin. Wisconsin Academy of Science and Arts*, vol. iii, p. 45.

† *Geology of Wisconsin*, vol. iv, p. 575.

‡ The Penokee iron-bearing series of Michigan and Wisconsin. *Mon. xix, U. S. Geol. Survey*, p. 461.

§ According to L. L. HUBBARD, state geologist of Michigan, this subsidence began early in the Keweenawan, and was continued during the accumulation of the 8,000 feet of coarse conglomerate on Keweenaw point. *Proceedings Lake Superior Mining Institute*, ii, p. 96, 1894.

disappear in some directions sooner than in others. There can be no doubt that under favorable conditions the surface eruptives flowed for many miles, and that in other conditions they were shut out, and a continuous series of fragmental strata was the result. The fine, red conglomerates and the red sandstones and shales were extended to great distances toward the southwest, and have been penetrated by deep wells at Minneapolis, Belle Plaine, Mankato, Hastings, Red Wing and other points, where they have been found in some instances, so thick that they constituted an effectual barrier against the further sinking of the wells.

Age of the Puckwunge conglomerate and sandstone. As in the eastern part of the United States, the term Potsdam has been applied, in the Northwest, to both of these sandstones, *i. e.*, to the quartzyte overlying the Puckwunge conglomerate, which has also had the names Sioux quartzyte, Baraboo quartzyte, Barron County quartzyte, and to the sandstones lying above the trap rocks, containing an Upper Cambian fauna which, in Minnesota, has been divided between Hinckley and St. Croix. From this circumstance considerable confusion of nomenclature has resulted. There is no doubt, however, that in the midst of what in some places is a continuous series of similar sandstone strata, the traps of the Manitou were interposed, thus affording an important character for dividing the sandstone into two parts. It also seems probable that even where no actual eruption occurred the cotemporary sandstone deposits were considerably affected in composition, and that, in others, the lower strata were hardened and cemented into quartzitic strata by the chemical action attending volcanic ejection in some adjoining portion of the ocean. If it be inquired what portion of this series is represented at Potsdam, N. Y., where the name was first applied to any part of this sandstone, there need be little hesitation in answering—to the earlier. Hence it is more in keeping with the practice of the best authority in geological nomenclature to restrict the term Potsdam to the quartzitic sandstone which, about lake Superior, underlies the traps of the Manitou eruptives and overlies the Puckwunge conglomerate, *i. e.*, to the sandstone seen at a mile west of Grand Portage village, and in Grand Portage island, to the quartzyte seen near New Ulm and in Cottonwood county, to the quartzyte in Pipestone county, and to the equivalents of this in the various deep wells. In some of the deep wells in the southern part of the state an enormous thickness of red shale and sandstone has been encountered, and this is supposed to be due to cotemporary volcanic action in such contiguity that the detrital and volcanic debris was colored by the ferruginous oxidation which rapidly pervades superficial volcanic ejections; but, owing to the occurrence of similar red shale in these lower quartzytes and sandstones, there must have been an earlier source for such sediment. There is here an indication of eruptive action in the central part of the state during the prevalence of what has been noted as the

Animikie revolution in the northeastern part of the state. Such sediments might constitute the transition link of the Animikie fragmentals in the central part of the state to the lower horizons of the Puckwunge (Potsdam). Still, it is at present impossible to refer this red sandstone and shale, as developed in several of the deep wells in the central part of the state, with certainty to either horizon.

The igneous rocks of the Taconic. The igneous rocks of the Taconic have been included *en masse* in the Keweenawan, and it is best to employ that designation with its original definition, rather than restrict its significance to include only the eruptives which accompanied and followed the clastic base of the Keweenawan.* But in order to avoid being misunderstood, and to insure definiteness to our desciptions, these eruptives will be divided into two general groups, with new names, viz.:

Cabotian: To include the gabbro and cotemporary accompanying red rock and their surface lavas and all their dikes and sills. These igneous rocks are associated with, but in date followed, the Animikie clastic rocks, and preceded the Puckwunge conglomerate, their debris being found in that conglomerate. This term is the designation given by Buchette to the mountain ranges on the north shore of lake Superior.†

Manitou: To include the cotemporary igneous rocks that accompanied and followed the Puckwunge conglomerate, whether surface flows, sills or dikes, extending to the top of the Keweenawan igneous rocks. This name is that of a river entering lake Superior in Minnesota.

The clastics that are associated with the Cabotian igneous rocks are of Animikie age, to the bottom of the Puckwunge conglomerate. Those which were cotemporary with the Manitou are of late Potsdam age. These graduate upward to sandstones free from igneous rocks, and to pure quartz sandstones, viz., the Hinckley and St. Croix sandstones.

Possible pre-gabbro eruptives. There are some reasons, mentioned under the paragraph which treats of the clastic strata of the Taconic, for believing there was some, probably gentle, eruptive action, after the substantial close of what we know of the Animikie, earlier than the convulsion which gave origin to the gabbro; and, further, that these eruptives were accompanied by some detrital accumulation. In the absence of definite facts that bear unmistakably on this point, it will be better to omit here further reference to these problematical eruptives, and to begin this description of the Cabotian igneous rocks with an account of the gabbro.

The Cabotian epoch of eruption. In superficial area, amounting to about 2,300 square miles within the state, in the associated problems of origin, date of intrusion, structural relations with older and also with more recent rocks, in variations of its

* This restriction was once suggested by the writer. *American Geologist*, xvi, 333, 1895.

† "During this distance the St. Louis river, a stream of prime magnitude, bursts through the high trap range of what Bouchette calls the Cabotian mountains, being a continuation of the upheavals of the north shore of lake Superior." SCHOOLCRAFT, in *Summany Narrative of an Exploratory Expedition to the Sources of the Mississippi River*, 1854, p. 110.

own internal structure and composition, as well as in the number of petrographic principles illustrated, the gabbro surpasses any other member of the Taconic, and perhaps equals in interest the granites of the Archean. Being an igneous rock of the opposite end of the magmatic scale it offers a new set of petrographical principles, and, with its attendant accidents of contact, exceptions and variations, it serves to add a large chapter to the petrographic geology of the state.

The numerous problems arising from the gabbro cannot all be considered as solved by the examinations the survey has given to them. There is a large uncropped field for the future student to enter upon. The structural discussion which follows is a tentative effort to set forth and to explain the leading facts of the gabbro on a general hypothesis, which is at the same time supported by all the special facts which are in our possession, or at least is not known to contravene them.

The extension of the gabbro toward the east. The eastern extension of the gabbro mass has sometimes been limited in the vicinity of East Greenwood lake, T. 64-2 E., and that approximately expresses the eastern limit of the continuous surface outcrop of the great body of the gabbro. At a short distance east of this lake it becomes covered by later diabasic flows, or loses itself in a series of sills and dikes that penetrate the Animikie. From Gunflint lake to Pigeon point the Animikie is thus affected. In some cases the body of the gabbro comes within a few hundred feet of the most southern mass of the Animikie bluffs, the Animikie having a dip southerly so as to throw it below the gabbro. This is particularly the case at Loon lake (south of Gunflint lake), where coarse characteristic gabbro is within 150 feet of the Animikie bluff, and the irresistible inference is that the great sills of diabase which are then seen in the Animikie at lower levels, and which are themselves sometimes intermediate petrographically between gabbro and diabase, are only apophyses from the gabbro. Such sills are of all dimensions, from one or two feet to fifty and more feet in thickness. Owing to the low dip of the Animikie, and to its easy removal by natural causes, it is seldom seen to persist on the tops of these mono-clinal hills, but almost everywhere the usual surface rock is that of one of these sills. This diabase-gabbro, therefore, might be said, in general, to extend much further east and north than the limit usually assigned to the gabbro itself. Indeed, it is very probable that even within the gabbro body, along the northern limit of surface continuity, there exists still intact much of the Animikie, and that such beds would be found on sinking a drill through the gabbro. Where these great sills constitute the representative of the gabbro, as at Rove lake, Mountain lake, Fowl lake and eastward into Canada, the country is generally very much broken, the mono-clinal hills and ridges rising steeply from 200 to 400 feet from the valleys on the north, but sloping more gently from their summits to the valleys on the south, the topography being due to the gentle slope of the Animikie dip but preserved by the greater endurance of the Logan sills, the latter still occupying by far the greater part of the superficies. It is in this portion of the northern border of the gabbro that the Animikie is very rigid and quartzose although slaty and easily removable by reason of its horizontal fissility and its frequent jointage. Into such a rock, undergoing upheaval and fracture, an igneous rock would farthest penetrate along planes of its easy parting, which, in this case, was along the sedimentary planes of slatiness. Some of the sills thus formed can be seen to be continuous occasionally for several miles, but generally they sink away and are replaced by others a little further north or south, after running less than two miles. As soon, however, as this quartzose and slaty member of the Animikie is replaced, at the point of intrusion of the gabbro, by the fragile Grand Portage graywacke, which breaks as easily in one direction as another, the form of the molten intrusion is changed into great vertical dikes, and these prevail in the Indian Reservation at Grand Portage. Such dikes form the mountainous features of the Grand Portage region. They are sometimes 100 or 200 feet wide, and they stand above the surrounding valleys 400 to 800 feet high, with sheer vertical walls of rock toward the top. By degradation of the enclosing graywacke the dikes have been uncovered and left bare. Mount Josephine, which stands near lake Superior and rises 703 feet above its surface, is a specimen of these dikes, but it is inclosed in the slates rather than in the graywacke.

The gabbro intrusion extends thus to Pigeon point, where it is shown to be of the same date as the great gabbro mass further west, by the effect it has on the Animikie, producing the red rock of Pigeon point, the crystalline debris from which is found in the Puckwunge conglomerate at the foot of Grand Portage island. The same red rock is visible in some of the hills near Grand Portage village, also at the east side of mount Josephine, and, according to Dr. J. G. Norwood, on the Pigeon river where these dikes are exposed by that stream.* How much further east this igneous intrusion extends, it is not at present possible to state. It is true, however, that the same kind of topography and the same kind of sills in the Animikie with occasional red rock areas, continue to Thunder bay and Silver islet. At the latter place red quartz-porphyry pebbles are found in the conglomerate at the bottom of the sandstone which lies non-conformably on the Animikie. Hence, it is reasonable to infer the existence of quartz-porphyry in that region produced by the same cause as at Pigeon point.

The extension of the gabbro toward the west. The western limit of the gabbro is represented, on our plates, to run southward across St. Louis county to the vicinity of Short Line park, a few miles west of Duluth. But that is a boundary that is

* Dr. Norwood's description and illustrations are on pages 407, 408, of Owen's report on the *Geology of Wisconsin, Iowa and Minnesota*, 1852.

wholly conjectural. It is simply the boundary of the most western line of outcropping. The rock disappears beneath the drift. The character of the rock at these western outcrops indicates that they are not "peripheral." The rock is coarse and rough. The gabbro may extend many miles further, underlying the whole Cloquet valley, which is also deeply buried under drift, and crossing the St. Louis valley north from Knife falls. It may even extend as far west as to include the gabbro which is seen in the northwestern part of Morrison county, for there is but one outcrop of the underlying formations between the Cloquet river and the Long Prairie river. That is a quartzyte, seen in Aitkin county, as described by Mr. Upham, and is probably of later date than the gabbro. If thus extended the gabbro belt would pass north of Knife falls, and the hills of gabbro seen at Short Line park would fall into the same category as the Sawteeth mountains, and could be classed with the Beaver Bay diabase, to which they show a general petrographic alliance, having characters indicative of surface flow. However, even with such a westward extension, the gabbro probably dies out in that direction in the same manner as toward the east, *i. e.*, by a diminishing series of dikes through the older rocks.

The southern limit of the gabbro. This has thus been described by Mr. Elftman:* "The southern boundary of the gabbro is irregular on account of the invasions of other members of the Keweenawan series. From the south side of East Greenwood lake the boundary passes westward for thirty miles and turns south and east through Brulé lake along the Brulé River valley to the east side of T. 63 N., R. 1 W. In the vicinity of Brulé mountain and Eagle mountain, the limit of the gabbro zigzags and finally follows a southwesterly course through sec. 6, T. 62 N., R. 2 W., and through sec. 15, T. 62 N., R. 4 W., on the east branch of the Temperance river; continuing westward it passes through the central part of T. 60 N., R. 6 W., between lakes Harriet and Bellissima; thence through the southeastern part of T. 60 N., R. 7 W., and between West Greenwood lake and Greenwood mountain, in T. 58 N., R. 10 W. At the last locality it turns sharply toward the south, passes near the northwest corner of sec. 19, T. 55 N., R. 11 W., and from there continues in a southwesterly direction to Duluth. These boundaries give the widest areal distribution of the gabbro. Within this area are other rocks, some of which are quite extensive and nearly all of later geologic age. The chief area of this kind is the region west and southwest of Brulé lake."

Along the northern and northwestern side of the great gabbro mass, the gabbro is plainly intrusive on the older formations, from the Animikie downward to the oldest of the Archean. On the southern and eastern border it is penetrated by and

* *American Geologist*, vol. xxii, p. 132, 1898.

penetrates in a confused manner the red rock, with which it alternates both structurally and areally. Large bosses and areas of the red rock, frequently granitic, penetrate the gabbro, and send dikes into it, the dikes sometimes running for several miles from the parent mass. According to Mr. Elftman, gabbro dikes are not known to cut the red rock, but this may be attributed, in a measure, to the assignment by him of such dikes to a supposed later intrusion of diabase, since the gabbro presents petrographic characters resembling those of diabase, when it acts as an intrusive in other rocks. The Beaver Bay diabase, which is considered to be the first great flow-stratum from the parent gabbro, carries isolated pieces of red rock, as shown in the chapter on Lake county. At Duluth, while the gabbro in the main lies under and involves the red rock, there are stringers and isolated red rock areas in the gabbro. The appearances, both at Duluth and at Beaver bay, are explicable by supposing the gabbro and the red rock were simultaneously in a state of mobility, allowing at the same time for the greater liquidity of a basic magma under complete fusion, and for the greater penetrating capacity of the acid magma, in a condition of aqueo-igneous fusion or plasticity.

The structural peculiarities of the gabbro. The Logan sills. Dr. A. C. Lawson gave this name to the great sills which, along the international boundary and thence to Thunder bay, lie in the bedding planes of the Animikie and greatly increase its aggregate thickness.* That these sills are cotemporary offshoots from the gabbro mass is sufficiently demonstrated by their mutual proximity and their similar petrographic characters. One of the greatest sills known is that of mount Reunion (No. 2064). It has a thickness of about 100 feet, and crowns the summit of a bluff of Animikie, facing north, which rises somewhat over 400 feet above the level of Rove lake. In this rock the augite is of two periods of development, a character not uncommon in the gabbro. The greater part of it is in rather small roundish grains that preceded the plagioclase, but there are a few larger grains that followed the plagioclase, since they embrace the plagioclase ophitically. Several instances occur of the inclusion of olivine in the augite. A little quartz, evidently of secondary origin, is in the angular spaces between the plagioclases, and also is in granophyric intergrowth with a feldspar which itself also appears to be of secondary origin. In several other instances (Nos. 296, 297, 300, 308, etc.) the same petrographic characters have been found in these greater sills, and in one or two of the great dikes that are probably cotemporary with the gabbro, at and near Carlton, at the extreme southwestern limit of the gabbro. Still, it appears that in many instances—and this seems to be the case when the dikes and sills are narrow—the augite is wholly later in date than the plagioclase, and displays only the ophitic relation. It is to be inferred,

* *Bulletin viii*, p. 48, 1893.

therefore, that when the gabbro magma consolidated in narrow dikes, or in large surface flows, there was some force that restrained the first generation of augite (contemporary with or earlier than the plagioclase) and only allowed it to form ophitically, after the generation of all the other minerals; but that in some cases the conditions were not sufficiently pronounced and uniform, and, as in many of the great sills, both generations of augite are seen. Hence, the characteristic diabasic structure is an incident of consolidation, and does not denote any difference in character, origin or date of the magma from which it resulted, by which the resultant rock can be differentiated, genetically or chronologically, from the gabbro. Most of the later eruptions of the Keweenawan coming probably from the same source as the sills of the Animikie, being of less volume, took the petrographic characters of diabase, as will be seen by examining the chapters devoted to petrography.

The Logan sills were at first believed to be, like the surface flows of the Keweenawan, of the same date as the sedimentary strata between which they lie. This was the view of Bell, Irving, and, indeed, of all geologists until quite recently, the writer included; and it was for this reason that on seeing the gabbro occupying a position low down in the "Animikie" at Chub (Akeley) lake, the age of the gabbro in its commencement was said to be near the bottom of the Animikie.* Although the nature of some of these sills was recognized by a few geologists earlier, especially by Mr. E. D. Ingall, of the Canadian survey,† it was not till 1893 that their true age and geological significance were fully recognized. This was by Dr. Lawson, who stated as below, the evidence that these sills are intrusive within the slates.

I. The trap sheets associated with the Animikie strata are not volcanic flows, because of the combination of the following facts:

1. They are simple geological units, not a series of overlapping sheets.
2. They are flat, with uniform thickness over areas more than 100 square miles in extent, and, where inclined, the dip is due essentially to faulting and tilting.
3. There are no pyroclastic rocks associated with them.
4. They are never glassy.
5. They are never amygdaloidal.
6. They exhibit no flow structure.
7. They have no ropy or wrinkled surface.
8. They have no lava-breccia associated with them.
9. They came in contact with the slates after the latter were hard and brittle and had acquired their cleavage, yet they never repose upon a surface which has been exposed to sub-aerial weathering.

II. They are intrusive sills because of the combination of the following facts:

1. They are strictly analogous to the great dikes of the region: (*a*) In their general relations to the adjacent rocks and in their field aspect. (*b*) In that both the upper and lower sides of the sheets have the facies of a dense aphanitic rock, which grades towards the middle into a coarsely crystalline rock.
2. They have a practically uniform thickness over large areas.
3. The columnar structure extends from lower surface to upper surface, as it does from wall to wall in the dikes.
4. They intersected the strata above and below them after the latter had been hard and brittle.
5. They may be observed in direct continuity with dikes.

* *Sixteenth Annual Report*, p. 85, 1887 [1888]. Notwithstanding this, the first description of an intrusive sill in the Animikie was penned by J. G. Norwood, in his report to D. D. Owen, p. 404, who also gave an illustration. He also described and illustrated in the same report the connection between the dikes and the "crowning overflow." The writer described an Animikie sill in Wauswaugoning bay, in 1878. *Ninth Annual Report*, 1881, p. 63.

† Descriptive sketch of the *Physical Geography and Geology of Canada*, 1884, pp. 21, 22.

6. They pass from one horizon to another.
7. The bottom of the sedimentary strata above them, wherever it is observable, is a freshly ruptured surface.
8. Apophyses of the trap pass from the main sheet into the cracks of the slate above and below.
9. The trap sheets, particularly at the upper contact, hold included fragments of the overlying slates.
10. They locally alter the slates above and below them.

Besides the sills, which date from the gabbro, there may be others of later date, and to these will apply the argument of Lawson, that they are younger than the Keweenawan. But no data are as yet at hand to warrant an attempt to separate such sills from those of the age of the gabbro.

The Grand Portage dikes. There are at least two systems of dikes in the vicinity of Grand Portage. This is attested not only by the observations of this survey, but also by those of Norwood, who examined this region for the Owen survey. The general trend of the most of the great dikes is toward the northeast by east, but that which forms Hat point, culminating in mount Josephine, is nearly at right angles with that direction. Much of the rock in the mount Josephine hill, south from the summit, has a basaltic columnar structure, the columns standing vertical, indicating that a dike here is merged into a sill. Several of these great dikes, which are several hundred feet wide, and sometimes rise above the adjoining slates with vertical walls from 50 to 100 feet, are noticeably crossed by a series of smaller dikes running nearly at right angles to them.

The individual great dikes cannot be assigned to different dates except by some careful field examination more detailed than it has yet been possible to give the region. Yet it is evident from general considerations that some are older than the others, for they produced the red rock which has supplied debris to the Puckwunge conglomerate, while the younger cut some of the amygdaloids which lie upon that conglomerate. Some of the latter can be seen on Grand Portage island and on the points west from Grand Portage bay. There is an interesting problem connected with these dikes which must be left for the future student to solve. The petrographical study which has been given these dikes seems to afford no criterion for discriminating them, for some of the younger, as well as the older, present the augite cotemporary with or earlier than the plagioclase, a characteristic which is sometimes said to belong to gabbro.

Effect on the Animikie—the red rock. It has already been stated, in describing the strike of the Animikie rocks, that the Animikie formation is completely lost, as such, in the gabbro mass. Observations made on Pigeon Point peninsula at mount Josephine, on one of the islands of the Lucille group (south of Pigeon point), at Duluth, at Brulé lake, have now well demonstrated that the Animikie is converted into the "red rock," so called, which extends from the place at which the Animikie disappears in the "gabbro flood," with a nearly continuous surface band to Duluth.*

*The phenomena at Pigeon point have been discussed by W. S. BAYLEY in a bulletin of the U. S. Geol. Survey, viz., No. 109, 1893.

That this red rock is in some way dependent on the Keweenawan is indicated by its non-occurrence elsewhere than in connection with the Keweenawan. That in all its phases, which sometimes reach a crystalline condition equal to that of granite, it has resulted from the fusion of an acid rock, is a legitimate inference. It may hence be accepted as a fair illustration of the origin of granite. It is the same which Irving called augite-granite, although augite is a more rare mineral in its constitution than has been supposed. It is not to be presumed that the fusion of the Animikie was necessarily the only source of this late granite. The tremendous agitation which gave origin to the gabbro probably affected the rock on which the Animikie lies, and it may have been fused in like manner and its contribution to the fused mass, when acid, went to swell the volume of the red rock, and when basic may have been added to the gabbro.

Neither is it to be assumed that this fusion was a mere surface effect, due to the overlie and heat generated by the gabbro on the Animikie from above downward. Indeed, it is noteworthy that the bosses of the red rock, where they seem to be *in situ* of their formation, penetrate to greater depths and show by their behavior that their primitive seats are below the surfaces where they occur. Sometimes the red rock is struck, as at the mining shaft on the island south of Pigeon point, below a greater or less thickness of Animikie strata which are but slightly altered. When the red rock can be traced by successive steps of petrographic transition into the Animikie in place, the red rock concerned is not a granite, but a red quartz-porphyry, or keratophyre, as in the low red-rock knob on the south side of Pigeon point. The greater crystallization is not on the side toward the Animikie, but on those sides most remote. Most of the red rock dikes and the surface flows are to be considered, therefore, as peripheral manifestations of a greater volume, and as suddenly cooled portions escaping from a magma which, congealing slowly, gave source to the augite granite. Hence the Animikie was fused from below by the gabbro mass and not from above. The gabbro, as we see it, lies on and penetrates the Animikie, but the action of this intrusion, and the distribution of the red rock, show that the intensity of alteration was seated below all the Animikie of which we have knowledge, and hence that the bottom of the Animikie suffered the transformation before the top was involved. Therefore, while in the main contemporary with gabbro, sometimes penetrating it, sometimes penetrated by it and sometimes mixing with it so intimately as to constitute intermediate rocks, such as "orthoclase gabbro" of Irving, and "hornblende gabbro" of Streng,* and although at numerous points the dependent genetic relation which the red rock bears to the fusion of the Animikie can be shown by ocular demonstration, it must be allowed that both

** Eleventh Annual Report, Minnesota Survey*, p. 51.

the source and the cause of the red rock may have been deep-seated, and may have involved other formations than the Animikie.

If this general conception of the origin and date of the red rock be admitted, the surface distribution which it shows in Minnesota, and, so far as known, all the special features of contact, flowage, intrusion and alternation with the gabbro and the cotemporary diabases, are easily apprehended.

In the main, the line of strike of the Animikie from Pigeon point to Duluth is represented by the red rock belt. It is certain that the undisturbed line of strike of the Animikie leaves the gabbro area and runs more westward, constituting the Mesabi iron range. It must therefore be understood that the strike of the red rock belt further south, so as to reach Duluth, marks a line of upheaval through the body of the Animikie area, really constituting another strike-line, or fracture line, dependent, not on the earlier existence of a shore line, but on the direction of a zone of dynamic fusion of later date. This red rock belt comprises the water divide. From it streams flow north and south—toward the north across the main gabbro area and on to the Archean, toward the south across the later diabases, etc., of the Keweenawan, into the area of the sandstones of the lake Superior valley. At Duluth the main gabbro area unites with and blends into the great Beaver Bay diabase, lying sometimes upon the red rock and sometimes on metamorphic rocks referred to the Animikie. It is probable that this relation occurs at other places toward the northeast, especially in St. Louis county, but they have not been observed, and therefore the red rock is considered as a continuous belt, while in many places it is known that the gabbro is separated from the Beaver Bay diabase by a wide tract of red rock.

The greater endurance of the red rock may be in part the cause of this greater elevation, and it may be in part due to a greater original elevation of the Animikie. The latter is indicated by the fact that toward the east this greater elevation blends in with the area of the Animikie, and its sills in Cook county, as the gabbro area becomes smaller and narrower. From the point at which the present water divide crosses the international boundary, between North and South lakes, the upper waters of Pigeon river, including the lakes of the international boundary, are turned eastward along the north side of this belt of greater elevation to the vicinity of South Fowl lake, below which point the Pigeon river begins its tumultuous descent to lake Superior, crossing the belt of elevation at its lowest (eroded) passage, and often running in a sharp preglacial gorge-like valley several hundred feet below the adjoining summits.

The Beaver Bay diabase. This term is not used in exactly the sense employed by Irving, although its rocks are embraced, in general, in Irving's Beaver Bay group. This diabase has an intimate connection with the red rock, and was apparently cotemporary with the gabbro and the red rock. It is believed to be due to the first (and the greatest) flow-movement from the gabbro mass toward the Lake Superior basin. If there were lavas that preceded it they were unimportant, and of the nature of volcanic ejections, superficial, local and easily removed or reincorporated when the general motion began. It contains many anorthosyte or feldspar masses, and a few of red rock. It is the matrix which encloses the boulders forming a great pudding-stone seen near Beaver bay at different points. Petrographically it is usually a diabase, in that its structure is ophitic, but this is not always the case. Its thickness is sometimes several hundred feet. In many places it has been called gabbro, as at Short Line park, near Duluth, where it not only shows the banded structure seen sometimes in the gabbro, and locally carries a notable amount of iron ore, but is also seen to be vesicular, like a surface flow.* It has an irregular and sometimes a gradational contact on the red rock, quite similar to that of the gabbro on the red rock. Such irregularities are common in the country about South Brulé lake and eastward. It was molten at about the same time as the red rock, as shown by an inspection of the relations of these two rocks about the shore of Beaver bay, yet it is cut by the red rock, and is the bearer of detached pieces of the same. The rock of the Great Palisades lies upon it, but it forms the crest of the Sawteeth mountains.

In moving from the area of the gabbro mass this sheet of diabase first encountered the Animikie, which is now represented by the red rock belt. If this rock occupied the prominence which it does at the present time, the diabase, once having surrounded it, would have flowed rapidly down the southern decline, leaving a comparatively thin covering over the red rock obstruction. If the movement continued long, as is probable, the action of the red rock was to form a kind of reef over which the diabase must have passed more quickly and in an attenuated volume, but further south, gathering in greater amount, was not only slower to solidify, but on complete solidification assumed more nearly the petrographic characters of the parent mass. Therefore, ascending the streams that enter lake Superior, such as Poplar river, or Temperance river, the observer comes upon coarse-grained conditions of this rock which are not distinguishable from the real gabbro, and such phases also appear at the shore line of lake Superior in the vicinity of Beaver bay, as well as at and near Duluth. During the lapse of the ages since this flow took place, the thin surface remnant which was left on the red rock belt has been destroyed and wholly removed, thus isolating the Beaver Bay diabase from its parent mass and constituting it the "great basal flow" of the Keweenawan defined by Irving.

*By Mr. Elftman this has been included in the later surface lavas of the Manitou series. *American Geologist*, vol. xxii, plate VII, September, 1898.

The removal of the superficial portion of the gabbro batholyth left exposed to atmospheric action the body of the gabbro mass. It is not probable that this movement took place within the crust below the surface. The effect of atmospheric contact is visible in many places on this diabase, and the crystallization of the red rock in nearly all cases is not that of deep-seated congealation. The fact that what is left of this great sheet seldom exhibits distinct superficial phenomena can be attributed to the denudation of its accessible upper portions, and the same probably applies to explain the present condition of the surface of the gabbro area itself.

The feldspar masses, or "anorthosyte." The former of these terms seems to be preferable to the latter, because the term anorthosyte is quite extensively applied to the gabbro mass itself; whereas, the objects here intended to be meant are quite distinct from the ordinary condition of that mass. These have excited the perplexed observation of several geologists. They have been considered as intrusive and later than the diabase, as transported blocks derived from a foreign source and as indigenous in the rock in which they lie, while by Lawson they have been supposed to belong to the Archean, on which the Keweenawan is supposed to rest. By the writer they have always been considered a part of the Keweenawan, but how they acquired their present forms and positions, and what their relations to the gabbro proper, have been points which remained unsatisfactorily explained until quite recently.

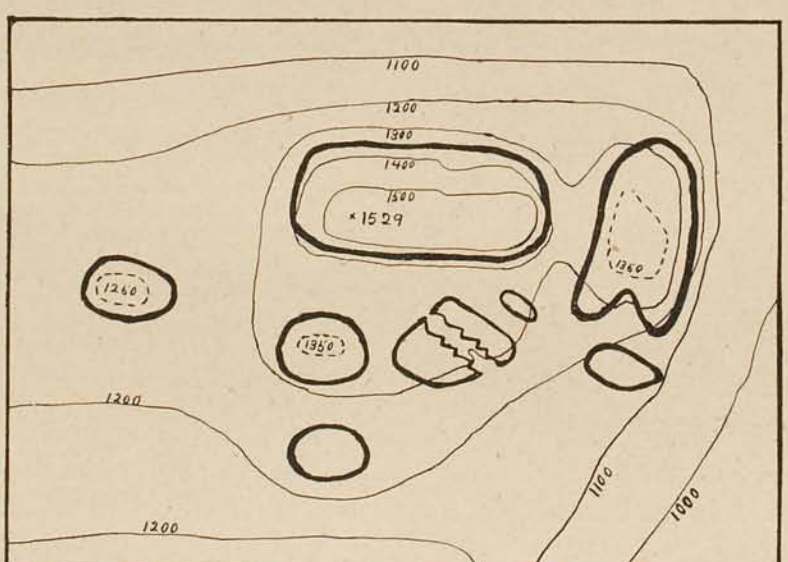

FIG. 2. DIAGRAM OF EXPOSURES FORMING THE TOP OF CARLTON PEAK.

Mr. Elftman's observations of Carlton peak are conclusive to show that at that place the feldspar masses were at first wholly surrounded by and now lie in and on the Beaver Bay diabase. At the shore of Beaver bay the diabase is about and over the feldspar masses. In the "pudding-stones" the feldspar masses are usually small and vary in mineral composition, and in the last case the diabase may have gathered up and transported masses of earlier cooled rock. Figure 2 is a contoured map of the summit of Carlton peak from Mr. Elftman's note book. The masses are isolated, and compose a small portion of the entire hill, some of them being 200 feet lower than others and separated by intervals of the ordinary diabase.

Within the main gabbro area are known several masses of similar rock, but they are not separable from the gabbro itself. They are phases of the formation resulting from a segregation and concentration of the feldspathic element. So far as observed they are not abruptly contrasted with the surrounding rock in a manner similar to the separation of the feldspar masses, but are associated about their peripheries with more or less of the ferro-magnesian minerals, and seem to grade into the general gabbro. At the same time the gabbro itself consists occasionally of nearly as pure feldspar as that of these isolated masses. When unweathered and coarsely crystalline, such areas do not attract attention, but are readily grouped with the general gabbro mass. The original habitat therefore of these feldspar masses may be assumed to be the gabbro itself. The manner of their formation was suggested to the writer by observing the accumulation of porphyritic crystals in a diabase at and westward from Gunflint lake. A coarsely porphyritic diabase forms a sill in the Animikie at the outlet of Gunflint lake. This sill is continuous westward, and is exposed along the Port Arthur, Duluth and Western railway. After a distance of about a mile toward the west, it was noticed that the feldspar crystals began to group themselves in couples, and in triplets, and then into irregular clusters. It was noted further that these clusters reached the size of a foot and more in diameter, and gave a blotched aspect to the diabase by reason of their lighter color. In traveling over the surface of this sill, which is denuded and at the same time much thickened, still larger areas of feldspar were seen, and it appeared as if numerous foreign masses were included in the diabase. These feldspar masses, however, were not sharply set off by rounded contours from the enclosing diabase, but presented angular projections and enlargements. It became apparent that it only required the continuation of such development in the ordinary diabase to reach the size and the purity of the masses seen at Beaver bay.*

If, then, it be admitted that these masses were indigenous in the gabbro, it remains only to account for their generally rounded contours and their greater number at Beaver bay. Generated in the gabbro mass before the Beaver Bay diabase left it, these masses must have had a tendency, on account of less specific gravity, to rise toward the top of the gabbro. It is quite reasonable to suppose that the minerals of that magma, as they took crystalline form, and if they became thus grouped, would, under unconstrained

* The generation of the feldspar masses from the general gabbro magma had previously been asserted by A. H. Elftman. *Twenty-second Annual Report*, p. 178, 1893 [1894].

conditions, tend to separate themselves according to their specific gravity. Those conditions must have been most favorable at that period when the cooling had not far advanced, but had reached the stage at which labradorite was generated and remained floating in the still molten mass. The cooling proceeded very slowly and must have taken place mainly after the severance of the Beaver Bay diabase. When that great partition occurred it of course removed only the upper portion of the gabbro, and must have carried along the major part of the feldspar masses. The inevitable result of such a motion must have been the collision of the feldspar masses upon each other and the rounding of their outlines. They seem to have been compressed and sometimes broken. They were, perhaps, not rigid at first, but still flexible, allowing the re-adjustment of the crystals, but also must have suffered numerous fractures and warpings. Through the fractures the molten diabase entered, forming diabase dikes, some of which still subsist, giving the impression of a later diabase intrusion. In this slow movement of the great molten sheet, the feldspar masses which it carried would first encounter obstructions from the underlying older rock. Becoming lodged, temporarily or permanently, the still liquid magma would flow past them, thus effectually removing them from contact with that particular part of the magma which gave them birth, and increasing the petrographic contrast between them and the diabase.

Muscovadyte. If the gabbro mass be considered as an individual, having phases of crystallization dependent on the stages of development, or as an epoch of geologic history for that part of the state in which it is found, the muscovadyte and the anorthosyte conditions occupy the extreme and opposite ends. One is so completely differentiated that it can hardly be traced to its parent stock, and has been some times denied all relationship in origin and in time with the source from which it sprang. The other is so non-differentiated and complex that in like manner it has been divorced from its offspring and has been assigned to an earlier geologic epoch and another method of genesis.

This rock presents protean characters, and its theoretical origin has had a curious and checkered history since the members of the survey began to study it. When this rock was first encountered it was called "muscovado rock" without any idea of its age and nature. Still, as it turns out, it had been examined earlier and had received the name "impure quartzyte." Again it was described as "noryte," and in one case it gave name to a point of land jutting into Gabimichigama lake, although at that place it is largely a fine-grained pyroxenic and biotite gneiss. It was found again to underlie, in form of angular fragments, a sheet of typical gabbro. It was found to form a gradual transition into biotite mica schist. At this stage of the investigation an effort was made to learn more definitely what distinctions were possible from a petrographic point of view. It became evident that the name had been applied to fragmental rocks and to igneous rocks, and that in the light of the close alliance of muscovadyte with the gabbro it would be best to restrict the term to a "peripheral phase" of the gabbro. With such interpretation Muscovado lake was named, which lies well within the gabbro area, because the most of its shores are composed of this rock. About this time the muscovadyte seen at Gabimichigama lake was traced through a slow gradation into the "greenstone" which occurs a few miles further east, and this transition has been observed since at other points. In several other cases the muscovadyte was noticed to be quite siliceous, and, acquiring a distinct sedimentary structure, was seen to change into ordinary greenwacke. Through greenwacke, therefore, it is linked with graywacke and the whole fragmental series. It was noted also, at numerous places, that, where the gabbro in bulk approached the eastern extension of the Animikie iron range, as that range was then understood and defined, the rock embracing the ore frequently was a form of muscovadyte, and that, in extreme metamorphism of the iron-bearing rock, the curious association was seen of the minerals olivine, quartz, magnetite. To these were added, usually in subordinate but varying proportions, biotite, diallage, augite, hypersthene and sometimes cummingtonite. Sometimes olivine was poikilitically related to quartz and magnetite, embracing both. Sometimes magnetite served the same office, and sometimes biotite, but usually hypersthene was latest to form, and hence surrounded all the other minerals in large crystals—and in favorable situations, as in vugs and veins, hypersthene reached the size of several inches. Prior to this the name Pewabic quartzyte was applied to the supposed base of the Animikie, where it exhibited this curious petrography; and under that name the supposed iron-bearing base of the Animikie was traced westward along the northern periphery of the gabbro to Birch lake and southwest from Birch lake to where the real Animikie appears. But the most interesting and important observation was made in the fall of 1897 at Disappointment lake. The iron ore, which occurs on the south shore and has been referred to the Animikie, is embraced in this rock muscovadyte. It is at this point and along the southwestern shores of the lake that had been observed the transition of muscovadyte into mica schist. This transition was again observed. This mica schist is conspicuously conglomeratic and occurs extensively about Snowbank lake, about a mile further northwest. The muscovadyte is also conglomeratic, losing this character, however, where it embraces the ore. There is hence a link which cannot be broken binding this ore with the older formation (Archean), and it hence bears exactly the same relation to the Keewatin as the jaspilyte seen in the conglomerate of the Upper Keewatin between Moose and Wood lakes. The gabbro is immediately adjacent and has an irregular superposition which resembles a transition to the muscovadyte. It appears, therefore, that muscovadyte has alliances in opposite directions, and without questioning here the contention that it is a part of the gabbro, and that the Pewabic quartzyte represents a silicified condition of the gabbro incidental to its peripheral position, it is claimed only that it has also undeniable and direct connection with the Keewatin.

With this observation as a key a considerable revolution has latterly been made in the interpretation of the iron ores which are associated with muscovadyte further southwest, and they have been assigned to the Keewatin, rather than to the Animikie. Their peculiar petrography is due to the gabbro metamorphism, and that will be discussed under the heading

So-called peripheral phases of the gabbro. There have been mentioned by different geologists a series of modifications in the gabbro, the same being supposed to be confined to the margins of the mass, and due to contacting on the older rocks. These are all connected with the muscovadyte mentioned above, and are, as it appears, only conditions of that rock. In some cases the gabbro is said to become granulitic, and fine-grained, with development of considerable quartz, hypersthene and biotite; it is said to become non-feldspathic, making a pyroxene-olivine rock, or peridotyte, and to be charged, in other places, with titanic iron ore. It exhibits great variations, not only in the relative proportions of the usual minerals, but in the successional order in which they were generated. There is so much variety that the characters of the rock show almost endless change, and no special classification seems possible. The minerals concerned are olivine, quartz, magnetite, labradorite, hypersthene, biotite, augite, diallage. The details in some instances are given in the chapter of this report devoted to the special petrography of the crystalline rocks; and they have been presented in considerable minuteness by Prof. W. S. Bayley.* Quartz and magnetite are present in greater quantities when the locality furnishing the specimen examined is from the immediate vicinity of some of the ore lenses above alluded to as closely connected with the rock muscovadyte. They are sometimes wanting, and then the rock presents some of the varieties usually referred to "granulitic gabbro," but there is no distinction that will hold, either structural or petrographic, between the granulitic gabbros, with their variations, and the iron-bearing muscovadyte. They are parts of the same variable rock mass, and belong originally in age to the clastic greenstone member of the Archean. It cannot be assumed that the muscovadyte, when free from quartz and magnetite, had a different origin from the same rock containing those minerals, for these minerals show all stages of increase, from zero to ninety-five per cent. When the rock consists essentially of the former it is a vitreous quartzyte, and when essentially of the latter

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* *Journal of Geology*, vol. ii, p. 814; vol. iv, p. 1. "The peripheral phases of the great gabbro mass of northeastern Minnesota."

it is a magnetite iron ore, frequently, but not always titaniferous. In both there are still small amounts of the other minerals.

These minerals are all secondary in the sense that they have resulted from the metamorphism of some others. This can be inferred not only from the facts to be seen in the field but also from a study of the minerals themselves with the microscope. It appears, therefore, that there was a prior rock whose profound alteration has generated all these varieties. It appears also that such rock while being one that could furnish, for the most part, the phase known as granulitic gabbro, or muscovadyte, was sometimes capable of furnishing a large amount of quartz, or again of quartz and magnetite. No rock is known having such qualities and such variations except the clastic greenstones. They were mainly a basic effusive, as already shown in discussing the Archean, but they vary by being fragmental, acquire quartz, which was chemically precipitated, or was added mechanically, hold the jaspilyte lodes, and sometimes are coarsely conglomeratic. The minerals of the intermediate rock and its structures, which stand between greenstone and gabbro, can all be produced by reforming the greenstones under conditions not allowing complete liquidity. The agent was not heat alone, and the condition of the magma was not that of simple dry fusion, but that of aqueo-igneous transformation. In this process there is not believed to have been any important transpositions of the original elements from their original places. The change that passed over the original rock when the result came to be the muscovadyte was a chemical reëstablishment of the old minerals native to the original greenstones, but lost through decay and age, or of their congeners.

If the nature and origin of the Archean greenstones be recalled for a moment, it will appear how well suited to the production of such a rock they were, and especially how easily, on metamorphism, they could produce all the peculiar phenomena seen in the association of olivine and quartz with labradorite, hypersthene, etc., in the iron-bearing muscovadyte. The tuffaceous elements, falling into the ocean from volcanic ejection, the quartz and magnetite as limonite falling at the same time or interruptedly with the volcanic ash from chemical precipitation, gave origin to a stratified greenstone, or green schist, in which were included the iron bodies now known as jaspilyte. The basic layers associated with the vitreous Pewabic quartzyte were "tuffaceous eruptive fragmental elements" of cotemporary date with the quartzyte in its original condition.

These muscovadyte phases are to be considered as specialized conditions of the old greenstones, but complex and nondifferentiated stages of the gabbro due to exceptional conditions which arrested complete regeneration. We here reach the most interesting, and perhaps the most important, part of this topic, viz.:

The origin of the gabbro. In the foregoing only the greenstone alliance of the muscovadyte has been presented. The investigations of the officers of the survey have led them face to face continually with the gabbro alliance of the same. Prof. Bayley, in one of his earlier discussions, was so impressed with this alliance that he grouped not only the original greenstone and the muscovadyte as parts of the gabbro (much altered), but also insisted that the siliceous or quartzyte phase was only a silicified part of the base of the gabbro;* and in support of the latter he quoted the observations of several officers of the United States geological survey. Several years ago it was agreed by the members of the Minnesota survey, after a petrographic examination of specimens from various localities, that the muscovadyte proper is a phase of the gabbro, and that the name should be restricted to apply only to a rock directly connected with and presumably derived from the gabbro.†

The following is quoted from the report where this conclusion is published:

"It would appear from the foregoing that the term muscovado rock (or muscovadyte) has been applied in the field to rocks of different stratigraphic position and origin. This has already been asserted by Mr. H. V. Winchell in the seventeenth annual report, pages 130, 131. It is also apparent that one of these is produced by the action of the gabbro upon the sedimentaries. It appears also probable that the southern belt of muscovado [*i. e.* that at Muscovado lake] is a phase of the gabbro proper, and that, if to either the name should be continued, it should be applied to this southern belt.

"There remains, however, this possibility, if not probability, that this southern muscovado represents the profound action of the true gabbro upon a basic Archean greenstone which has been brought to the surface in the midst of the gabbro area by a later fault. We have learned from numerous observations that all the rocks in this region have in some places been extensively faulted. It will be well, therefore, still, before adopting this duplicate theory of the origin of the so-called muscovado, to examine further critical specimens collected at points where it can be shown that the true gabbro was superposed upon a basic greenstone of Archean age."

So far as possible since that date the term has been so used; but on making an exhaustive microscopical examination of the specimens collected, and of the notes and descriptions of all the members of the survey, both published and unpublished, the conviction returns that the muscovadyte is also allied with the Archean.

To account for the gabbro, therefore, is to find some way to explain the conversion of an Archean greenstone with its siliceous accompaniments into that rock. There is only one recourse—metamorphism, carried to fusion and intrusive action. This is the same principle appealed to and already adopted to account for the Archean granites.

Besides these petrographic and special considerations indicating such genetic relation, there are some broader inferences to be drawn from the general geology of the northern part of the state.

1. The great area, the manner of occurrence of the gabbro body and its wholly crystalline condition, indicate that in method of genesis it is comparable to that of the igneous granites, and hence that it should be found in the zone of a dynamic strain, or at least in line of a metamorphic belt.

2. The earlier metamorphic belts in the northeastern part of the state trend northeast and southwest, hence, if the comparison hold good, the direction of the greater axis of the gabbro belt should extend northeast and southwest.

* *Nineteenth Report*, pp. 193-210.

† *Twenty-first Annual Report*, pp. 143-152, 1892 [1893].

3. The lines of granitic protrusion and intrusion are found to be limited, in their main dimensions and directions, by the known earlier existence of areas of acid fragmentals, only encroaching in the form of apophyses, and rarely, as rocks of intermediate acidity, on the areas of earlier basic rock. Hence, again, if the comparison hold good, the gabbro should be found in a belt of Archean basic rock, or in the extension of that belt.

The first two of these statements are so evident from a moment's examination that they need no amplification. It may be well, however, to call attention to the probable further westward extension of the gabbro than is usually represented, and in a direction more westerly. Its surface exposure is cut off by a heavy drift covering. It is likely also that the spur of the gabbro belt which appears at Duluth in large part belongs to the Beaver Bay diabase which left the main mass by a grand movement toward the basin now occupied by lake Superior, and hence that the main trend of the gabbro body runs to the north of Duluth and toward the mouth of the Cloquet river in the St. Louis valley. Toward the northeast the gabbro fades out by running into a series of sills and dikes in the Animikie, and in this form it appears for many miles in Canada, there being no general gabbro area free from the Animikie.

In respect to the third of the foregoing general comparisons, it should be noted, in the first instance, that the uniform directions of the metamorphic belts of extreme metamorphism, which are approximately outlined by the ranges of granite, show a tendency to change as they approach the basin of Lake Superior. This is more apparent after the epoch of the gabbro than before it. Whatever may have been the cause or causes of this shifting in the direction of the later zones of metamorphism and eruption, it is apparent that it resulted in the more definite outlining of that basin in the later stages of its geologic history. It is apparently in keeping with this gradual change in the lines of metamorphic intensity, that the gabbro has its more southerly position and its somewhat crescentic shape, with its concavity toward lake Superior. The question now arises whether, where the gabbro now occurs a belt of Archean greenstone formerly existed. The line of direction of the northerly boundary of the gabbro between Gunflint lake and Kawishiwi river (T. 63-9 W.) is in contact with greenstone continually, and it is in this interval that are found its muscovadyte phases. Further southwest, and to Birch lake, it lies alongside the eastern part of the White Iron Lake granite. But it is known that this granite was intrusive at an earlier date in greenstones at White Iron lake and southwestwardly at Birch lake. It is hence to be inferred that the general greenstone belt extended originally at least to Birch lake. At the south of Birch lake the Animikie reappears. It lies on the Keewatin along the southern slope of the Giant's range; and this Keewatin, largely of greenstone character, is known to continue westward to the western confines of the Mesabi Iron range. Here the country is also much drifted, but it can be assumed that the same formation is practically continuous at the surface as far as the central and western part of Carlton county, and to the western part of Morrison county, where it is again well known. Whether in some parts of this drifted area it is covered by the Animikie, is immaterial.

Toward the northeast, at and near Gunflint lake, where the Animikie again appears distinct from the muscovadyte and the gabbro, the Animikie lies on granite, and this relation continues northeastwardly, according to Mr. E. D. Ingall, for many miles into Canada. Hence, if the greenstone belt above mentioned continues further east, it must run below the Animikie along the south side of this granitic belt. Toward the east, north and northwest, therefore, it is fair to assume that the gabbro is in intimate relations with a greenstone belt. Toward the west it is covered by drift and the nature of the rock is unknown, but is probably the same as far as to western Carlton county. Toward the south and east the older rocks are hid by the Keweenawan. This is sufficient to show that, in all probability, the crescentic line of folding and of metamorphism which outlines roughly the gabbro area in Minnesota, intrenched on a prior existing belt of greenstone which seems, toward the northeast, to have passed below the Animikie but caused the penetration of the Animikie by many great sills and dikes, and toward the southwest, as seen about Carlton and Cloquet, to have sent similar dikes into the contiguous formation.

If the greenstone member of the Archean, the oldest known rock, be the source of the gabbro, and the gabbro be the source of the sills and dikes of the Animikie, an important corollary can be drawn. The greenstones, underlying the gneisses of the Archean and being older than any of the granites intrusive into them, are capable of furnishing, on any similar occasions of refusion throughout geologic history, not only bosses of gabbro, but dikes of diabase, even to the present time.

The Manitou epoch of eruption. After the removal of the Beaver Bay diabase from the body of the gabbro there appears to have been a period of tumultuous oceanic transportation during which was formed the Puckwunge conglomerate. For a short time the igneous forces were comparatively still, allowing the accumulation, especially on the south side of lake Superior, of great thicknesses of coarse conglomerate. But even during the age of this conglomerate, and especially during the formation of the sandstones that followed it, there were occasional and local lava flows which must have extended for many miles. After each epoch of these later eruptions the lava sheet was covered by a sandstone, often conglomeratic, derived principally from the disintegration of the previous trap sheet. This succession of igneous and fragmental rocks characterizes the Lower Keweenawan of Irving. It is apparently much thicker on the south side of lake Superior than on the north. A single conglomerate on the south side has been found to have a thickness of about 2,000 feet, and the total thickness of coarse conglomerate on Keweenaw point has been estimated at 8,000 feet. The beds of this horizon on the north side of the lake do not probably exceed 200 feet in thickness. The igneous lava flows that followed the great conglomerate epoch are also much thicker on the southern side than on the northern. In the former they are estimated by Irving at 33,000 to 35,000 feet at Montreal river, whereas in Minnesota they probable do not exceed 1,000 feet; while, if the Puckwunge conglomerate and all the other fragmentals, together with the Beaver Bay diabase and red rock, be united under the term Keweenawan, the total thickness in Minnesota would probably not exceed 3,000 feet, and certainly would not reach 5,000 feet. It is to the eruptives of the epoch following the Puckwunge conglomerate that is applied the name Manitou.

These lava sheets extend along the lake shore from near Baptism river to near Grand Marais, except where they are replaced by the Beaver Bay diabase, or by some of the intersheeted fragmentals. It is uncertain how much of the immediate shore line east of Grand Marais is occupied by these traps. There is some reason for believing that the so-called "black traps" of Irving, seen eastward from the mouth of the Brulé, are a portion of the Beaver Bay diabase. Some part of the shore west from Grand Portage bay, as far as to near Red Rock bay, is made by trap sheets of later date than the Puckwunge conglomerate. The geographic distribution of the parts of the Keweenawan at Grand Portage, and for some miles westward, cannot be said to be sufficiently studied. The question is complicated by the occurrence of diabase dikes of great thickness cutting even the latest of the known trap sheets, as may be witnessed at Grand Portage island.

As to the source of the diabase forming these later sheets, and also the later dikes, it may have been from the same great gabbro mass, which must have extended laterally, beneath the later rocks, to great distances, and which must have cooled with great slowness. Such dikes and sheets may also have originated from the Beaver Bay diabase itself before it became solidified. Whether from one or the other they are of later and later dates toward the east and may be, at the last, as late as the dikes cutting the Trenton limestone at Montreal, as suggested by Lawson.

THE PETROGRAPHIC GEOLOGY OF THE CRYSTALLINE ROCKS OF MINNESOTA.

By N. H. WINCHELL AND U. S. GRANT.

The following work is in keeping with the general plan which was adopted several years ago. The field numbers of the specimens are preserved. These numbers have been used to identify them in the various annual reports and in the several bulletins. The specimens, preserved in the university, will serve for many years to verify or correct the conclusions to which we have arrived. The intention has been to describe, with at least a classificatory designation, but usually with some exactness, and by means of microscopical examination of thin sections, every rock specimen that has been collected and reported with a field number in the annual reports, to which the student is referred for their field relations. In other places these lithological determinations are employed in the discussion of the systematic and areal geology, and in those chapters many new field observations will be found.

We have adopted the descriptions of other geologists whenever they have been sufficiently full and have served our purpose; but when our specimens did not answer to the descriptions published by others, or there was some doubt as to the identity of locality, we have made our own descriptions. It will be found that many of the field descriptions require correction, and that too, in some cases, when such descriptions were supplemented by some laboratory examination before publication. In some cases, also, some of the field numbers will be found missing from this enumeration. That is for the reason that the rocks represented were found to be of little importance or they were of doubtful relationship with the others, or because they are not found now in the collection.

Habitually we have given the megascopic and microscopic characters separately, and have made use of chemical analyses whenever possible, many of which are new.

The work is divided into two parts, viz.: *Part II*, which embraces all special petrographic facts, microscopic and descriptive, and *Part III*, which embraces such discussions and comparisons as to genesis and relationship as appeared to be the result of the foregoing, or to be germane to the *petrographic geology of the crystalline rocks of the state*. This, therefore, does not include the descriptive geology, which composes vol. iv, nor the systematic and structural geology which is given in Part I of this volume.

This work is based on the examination of about 3,000 microscopical thin sections. They were made by different assistants, and by M. C. Marchand, preparateur to the Museum d'Histoire Naturelle, Paris. The first thin section of rock ever made at the University of Minnesota was ground and mounted by the senior author of this in 1879, by the use of a lithologist's lathe procured of Prof. A. A. Julien, of New York.* Since that many other sections have been made on the same lathe by Messrs. Herrick, Terry, Oestlund, Wood, Meeds and Ogaard. It is run by the water-pressure derived from the city waterworks of Minneapolis; and from time to time some results of microscopical study have been published. We have had available as aids all the literature which has been published in this country bearing on the subjects investigated, and much of that of Europe. Our microscopes are, besides the original *Tolles microscope* purchased in 1879 and specially remodeled for petrography under the direction of Prof. Julien, an *Acme* lithologist's microscope made at Lancaster, Pennsylvania, and refitted by Bausch and Lomb, and a Nachet *Grand Modèle* with some recent attachments.

Finally, acknowledgments are due to Prof. A. Lacroix, of the Museum d'Histoire Naturelle, Paris, for assistance received during the year 1895, which was spent by the senior author at work in his laboratory on a series of Minnesota rocks. Many of the important and also of the special determinations have had the sanction of his approval. A second visit for the same purpose was made in 1898, and many suggestions were received again from Prof. Lacroix. We wish to record a lively appreciation of the enlightened generosity of the French republic in supporting at Paris such institutions as the Museum d'Histoire Naturelle, offered free to all naturalists for the research which they wish to carry on.

LIST OF PUBLICATIONS TO WHICH REFERENCE HAS FREQUENTLY BEEN MADE, BEARING ON THE PETROGRAPHY OF MINNESOTA, ARRANGED CHRONOLOGICALLY.

1871. J. H. KLOOS: Zeit. d. deutsch. geol. Gesell, xxiii, page 417 (with a map). Translation in the the tenth Minnesota Report.

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Abbreviations—

Ref.—References.
Meg.—Megascopic characters.
Mic.—Microscopic characters.

The method of labeling the specimens collected has been found very safe and permanent. It consists in mixing a solution of common shellac, such as can be got of a druggist, with some coloring material, and carefully placing the numbers on the specimens by hand. The alcohol rapidly evaporates from the shellac, which hardens, embracing the coloring material in the hardened mass. Such labels maintain their color and are insoluble in water. Specimens have been numbered as below.

The regular museum series, rocks, minerals and fossils, have their numbers in *red*, produced by mixing the shellac with "vermilion red."

The series of N. H. Winchell are marked with *blue* numbers, produced by mixing "indigo blue" with the dissolved shellac. Series from No. 1 to No. 2280. (These numbers are sometimes nearly or quite black.)

The series of A. Winchell are numbered in *black*. A mixture of shellac with India ink, and the figures also are followed by the letter W. Series from No. 1 to No. 990.

The samples collected and reported by H. V. Winchell are marked *pink*, formed by a mixture of vermilion red and white lead, and the numbers are followed by the letter H. Series, No. 1 to No. 542.

The samples collected by U. S. Grant are marked *green*, made by mixing Paris green with shellac, and the numbers are followed by G. Series, No. 1 to No. 1067.

The specimens of J. E. Spurr are numbered in *cream white*, and the numbers are followed by the letter S. Series, No. 1 to No. 231.

The specimens of A. D. Meeds are marked in *cream white*, and the numbers are followed by M. Series, No. 1 to No. 46.

The specimens of A. H. Elftman are marked in *white*, and the numbers are followed by the letter E, the series continuing from No. 1 to No. 767.

General Index to the Geographical Locations of the Rock Numbers of N. H. Winchell.

[The exact locations are given in connection with the descriptions.]

Nos. 1 to 293. Along the shore of lake Superior from Duluth to Pigeon point.

Nos. 293 to 435. From Grand Portage north and west along the international boundary to Burntside lake, thence to Vermilion lake and the Squagemaw bridge (at Embarras lake).

Nos. 436 to 442. Eastward from the Embarras lake, on the Mesabi Iron range.

Nos. 443 to 510. From Fond du Lac to Knife falls.

Nos. 511 to 641. From Duluth to Pigeon point, Isle Royale, Silver Islet (Thunder Bay) and return to Duluth.

Nos. 642 to 796. From Grand Marais northwestward to Ogishke Muncie lake, and thence southwestward to the mouth of Poplar river.

Nos. 797 to 806. Taylor's Falls, East St. Cloud, Watab.
Nos. 807 to 819. Fond du Lac and Duluth to Beaver Bay.
Nos. 820 to 829. Taylor's Falls and southward along the St. Croix river.
Nos. 830 to 838. Sioux Falls, S. D., New Ulm, etc.
Nos. 839 to 862. Sauk Rapids, Motley, Pike Rapids, Courtland (Nicollet county), Duluth, Sauk Centre.
Nos. 863 to 1000. Vermilion lake eastward to Fall lake, Birch lake, Kawishiwi river, Long lake.
Nos. 1001 to 1109. From Long lake eastward to Kekequabic and Ogishke Muncie lakes.
Nos. 1110 to 1140. Collected by Dr. Wadsworth about White Iron and Birch lakes.
Nos. 1141 to 1147. From the Marquette and Gogebic Iron ranges.
Nos. 1148 to 1215. From the original Huronian region in Canada.
Nos. 1216 to 1255. From the Marquette region.
Nos. 1256 to 1263. From the Gogebic Iron range.
Nos. 1264 to 1452. From Grand Marais to Brulé mountain, Gunflint lake, Akeley (Chub), Gabimichigama Ogishke Muncie, Kekequabic and Knife lakes to Tower.
Nos. 1453 to 1456. From Black River Falls, Wis.
Nos. 1457 to 1500. Collected by F. N. Stacy, northward from Gunflint lake.
Nos. 1501 to 1514. Tower and Ely.
Nos. 1515 to 1546. Redwood Falls, Pokegama falls, Duluth.
Nos. 1547 to 1572. Vicinity of Tower.
Nos. 1573 to 1606. Sudbury, North Bay and the Original Huronian region.
Nos. 1607 to 1614. Vicinity of Cloquet.
Nos. 1615 to 1626. Ely and vicinity.
Nos. 1627 to 1644. Mesabi Iron range, Republic mountain.
Nos. 1645 to 1669. Potsdam, N. Y., and the northern slopes of the Adirondacks.
Nos. 1670 to 1687. Little Falls and Philbrook, Morrison county.
Nos. 1688 to 1714. Mesabi Iron range.
Nos. 1715 to 1778. Kawishiwi river, Snowbank, Kekequabic, Knife, Zeta and Gabimichigama lakes.
Nos. 1779 to 1785. Eastward from Gabimichigama lake to Muscovado lake.
Nos. 1786 to 1806. Ely, Virginia, Duluth.
Nos. 1807 to 1859. Grand Marais eastward to Pigeon point and return to Grand Marais.
Nos. 1860 to 1906. From Grand Marais north on the Iron trail to Misquah hills, Brulé lake, Akeley (Chub) lake, Gunflint lake and Puckwunge valley.
Nos. 1907 to 1927. Iron mountain, Mich., Quinnesec falls, Republic mine.
Nos. 1928 to 1937. Keweenaw copper range, Calumet and Hecla.
Nos. 1938 to 1941. Gogebic range.
Nos. 1942 to 1953. Short Line Park, Cloquet.
Nos. 1954 to 1968. Ely, Soudan, Duluth.
Nos. 1969 to 1979. Carlton county.
Nos. 1980 to 2030. Ortonville, Vermilion lake.
Nos. 2031 to 2048. Knife and Saganaga lakes.
Nos. 2049 to 2065. Gunflint, Loon and Rove lakes.
Nos. 2066 to 2078. Puckwunge valley.
Nos. 2079 to 2091. Carlton county.
Nos. 2092 to 2113. Ely and Long lake.
Nos. 2114 to 2128. Long and Burntside lakes.
Nos. 2129 to 2134. Taylor's Falls.
Nos. 2135 to 2144. Mesabi Iron range.
Nos. 2145 to 2191. To Snowbank lake *via* Fall, Saturday, Urn, Bassimenan, Oak Point, Pine and Moose lakes.
Nos. 2192 to 2214. Snowbank and Disappointment lakes to Prairie portage.
Nos. 2215 to 2274. To Snowbank lake *via* Kawishiwi river, Triangle, Northwestern and Moose lakes.
Nos. 2275 to 2280. Vermilion lake and the "burnt forties."

Grand Divisions of the Coast Line.

Cabotian gabbro and Beaver Bay diabase:

Short Line Park to Duluth.

Splitrock river to the base of the Great Palisades.

Brulé river to the west side of Deronda bay.

As sills and dikes in the Animikie to Pigeon river and Pigeon point.

Later Cabotian surface flows:

Duluth to Splitrock river.

Grand Marias to Brulé river (with red rock).

Manitou flows [and Puckwunge conglomerate]:

Baptism river to Grand Marias.

Deronda bay to Grand Portage.