PART III.

MINERALOGY AND PETROLOGY OF MINNESOTA.

By N. H. WINCHELL.

(a) THE ROCK-FORMING MINERALS.

(1) *The White Minerals.*

Quartz. That mineral which is one of the most abundant, and which ordinarily appears most refractory, being infusible and insoluble in ordinary conditions, is one of the most mobile under the conditions that obtain in the rocky strata, and especially under the forces that cause metamorphism. Its changes are visible even in the most friable sandstones. When no other alteration is visible in some of the clastic rocks, the quartz grains are seen to be enclosed in a new sheath of quartz oriented in the same directions as the original grains. This has been shown by Irving and Van Hise in the case of many of the rocks of the lake Superior region,* and had been noted earlier by Sorby and by Bonney in the case of various European rocks. As this change is the first symptom of metamorphism in any clastic rock containing quartz, so it continues throughout the progress of metamorphism to be the most important and the most active. It proceeds so far that the first clastic grains, whose forms are wholly obliterated and which are entirely recrystallized, are those composed of quartz, and, when the alteration of the rock is completed, the last mineral to have been located in the new crystalline mass is uniformly quartz. It encloses all the other minerals, or at least it occupies those spaces that were last filled. When the feldspars are also metamorphosed, it sometimes penetrates them and fills the openings between their cleavages.

Quartz grains not only undergo enlargements by very slow and sometimes by insignificant increments to their borders under the gentle influence of ordinary temperatures, but they are powerfully affected when they come under the influence of igneous contact. Here they can be seen to become bipyramidal and to take up the rôle of phenocrysts in a quartz-porphyry (Nos. 619, 783, 784), while in the same rock mass, at a short distance from the contact, the clastic structure of the quartz grains is preserved (Nos. 264, 1838, 1839).

**Bulletin viii*, U. S. Geol. Survey, 1884.

It is obvious, therefore, that in many cases it is wholly impossible to state whether a grain of quartz seen in a given rock section is original or secondary, in the usual petrographical signification of those terms. There might be discovered, perhaps, by a very exhaustive study of the internal structures of quartz grains, and of the distribution of their minute inclusions, such differences between the original clastic grains and those grains which have been wholly rewrought under metamorphic agencies, that they could be distinguished, the one from the other. But we have not attempted any such examination. The fact that a quartz grain has been developed by new growth to fill the surrounding angular spaces, or that it encloses the other minerals of the rock, such as feldspar, mica or hornblende, has been considered sufficient indication of the later date of the quartz. In some such cases the borders between the old and the new quartz remain, marked by a more or less distinct band of ferruginous inclusions. Such borders, however, are found only in the least metamorphosed rocks. In far the greater number of instances the quartz of the crystalline rocks, whether metamorphic or igneous, is so completely changed that no trace remains of its original shapes.

Under metamorphism, quartz is quick to make its appearance. This seems to result in part from the dissolution of unstable compounds, such as volcanic ash, or undifferentiated volcanic glass, and in part from the superficial evaporation of silica-bearing alkaline waters. Fresh waters penetrating the rocks become alkaline. When heated, these waters not only take up silica, but also rise gently toward the surface, and, there evaporating, they part with their surplus silica, rendering the rocks through which they pass slightly more quartziferous. Thus veins are filled, and, to a limited extent, the enclosing rocks may have quartz supplied to their interstitial cavities. In the case, however, of the solid interior of a massive crystalline rock, such change, by the substitution of quartz for some of the constituent minerals, is so slow and so uncertain that it can be questioned whether it exist at all. No evidence of it has been found in the course of the foregoing petrographical investigation of the rocks of the state. When quartz is found to exist in any deep-seated crystalline rock, it seems to be necessary to allow that it existed there from the date of formation of the rock as such. It may be altered by metamorphic forces, as all the minerals may be, and new crystalline conditions and even new chemical combinations may have been imposed upon it, but it seems necessary to exclude the idea that changes of the relative amounts of the chemical elements have been effected. The interior of the oldest rocks known are exactly as fresh and as complete as rocks (excluding, of course, occasional abnormal conditions) as when they were first formed. When a deep-seated rock is metamorphosed its elements are recrystallized *in situ*; at least this is the case with the metamorphism of the Archean as exhibited in Minnesota.

We consider quartz as wholly a secondary mineral, when considered petrologically; that is to say, whether found in the acid rocks, such as granite, or in small amounts in the basic rocks, it has been through some earlier state and has been introduced into these places by some more or less fortuitous or accessory conditions in nature. In the acid crystalline rocks it is believed to have existed in clastic condition prior to the metamorphism, and in the basic rocks it originated either in the same way by the metamorphism of a basic clastic rock containing less quartz, or by contact with and the inclusion of some of the acid rocks. This opinion is based not only on the observations recorded in Part II of this volume, but on the results hitherto reached by experimentation in the artificial production of quartz by igneous fusion of other minerals and of rocks.* Never has quartz yet been found to result from the cooling of fused mineral matter, but its production through the action of natural pneumatolitic agencies is a matter of common observation. Artificially also quartz crystals have been produced in the presence of water at a high temperature under great pressure. Daubrée produced fine quartz crystals by subjecting common glass to heat in a closed vessel at a temperature of 320 degrees centigrade, the test extending through several weeks. The glass was transformed into a leafy kaolinic mass on the surface of which could be seen standing out so as to be perceived by the hand-glass hexagonal pyramids of quartz.

Friedel and Sarasin also produced quartz by employing a solution of gelatinous silica in a slightly alkaline liquid. In another experiment by the same chemists, conducted likewise in the presence of water under pressure, with a silicate of potash for the purpose of obtaining artificial orthoclase, crystallized quartz was formed. Tridymite and opal have also been formed artificially by various experimenters when operating in the wet way and under pressure. The only instance (which yet needs verification) of the production of quartz in the dry way is that of Hautefeuille, who produced a substance supposed to be quartz, but having different crystalline forms.

Quartz is therefore to be considered a mineral of that zone of the earth's crust to which water and the vapor of water are accessible. It seems to be precluded from the deep-seated original rocks, not only by the facts of field and microscopical observation, but also by the most obvious inference from the experiments that have been made for its production by dry heat. In all cases where, in the foregoing descriptions (Part II), quartz has been mentioned in an "igneous" rock, the rock containing it is either in immediate or approximate known contact with acid rocks, or the environment is such that such proximity of acid rocks is a reasonable inference (Nos. 672, 686). In numerous instances it occurs in the metamorphic clastic

*La plupart des nombreuses variétés de silice à structure cristalline, qui se rencontrent dans la nature, n'ont pu jusqu'au présent être reproduites artificiellement. On n'a pu refaire ni le quartz en large plages des granites, ni le quartz granulitique des granulites et microgranulitiques, ni le quartz globulaire, ni le quartz cunéiforme des pegmatites et micropegmatites, ni le quartz bipyramidé à formes raccourcies à angles arrondis, si commun et si caracteristiques dans les microgranulites, dans les porphyres et dans les roches volcaniques acides. *Synthèse des minéraux et des roches, p. 81. Fouqué et Michel Lévy.* Paris, 1882.

rocks and in the igneous rocks that have resulted from them through intense heat and pressure in the presence of moisture.

From this view of the origin of quartz, it follows that it is of secondary date in pegmatyte and micropegmatyte (Nos. 643, 672, 686) in the quartz mosaic that results from the devitrification of volcanic glass, whether acid or basic, and in the apobsidians and aporhyolytes of the Keweenawan. It also follows that in all rocks resulting from the crystallization of fragmentals, whether schists, gneisses or granites, quartz is in a secondary condition, however compactly and intimately it may be interlocked with the other minerals. The manner in which quartz develops poikilitically in the formation of granite from clastic debris is illustrated by rock No. 1039.

It follows, also, that there is very little "original" quartz. The only original minerals, in a broad sense, are those that composed the original and oldest rocks, viz., the massive greenstones of the Kawishiwin, or the oldest quartz-porphyry and its allies of the Lower Keewatin. Original quartz occurs in the latter but not in the former. By manifold chemical and mechanical transformations and perhaps by later chemical oceanic precipitation, the quartz that permeates all the later formations has been derived, whether those formations be clastic or igneous.

In a restricted sense, however, the term original is often applied to all the minerals of a rock perfectly and freshly crystalline, especially if it cooled from a molten condition, and the term secondary to those minerals that have resulted from the decay or alteration of the original minerals. There is, however, a degree of uncertainty and vagueness in the use of these terms in this sense, owing to the blending of the effects of original crystallization and of metamorphism and recrystallization.

Orthoclase is everywhere an accompaniment of quartz, and nearly all that has been stated regarding quartz is equally true of orthoclase. In one respect, however, they differ, viz.: an "altered" or a recrystallized grain of orthoclase is easily distinguished from an original one. In the quartz-porphyries of the Lower Keewatin (Nos. 2229, 2237, 2238) where quartz first appears, orthoclase also is found, but the crystals which it forms are fragmental, resorbed and clouded by alteration. They have the appearance of having suffered much abrasion and decay before they were finally embraced in solid rock. They are decayed throughout, evenly, as evinced by the uniform dissemination of many muscovite scales. While such a crystal is evidently *original* in all senses of that word, it is evidently not in its original condition. Pure, fresh orthoclase is free from such muscovite scales, and from all other alteration products, and is nearly as clear as quartz. So long as such a crystal of orthoclase maintains that flecked appearance evenly distributed through its whole mass it may be considered as an original mineral. But when, in a later period of its history, the rock mass in which it lies is subjected to metamorphic forces, becomes plastic, and is amenable to general chemical transformation, a great change takes place. The crystal becomes larger by the absorption of a portion of the surrounding matrix, which is also finely orthoclastic, and a rim of fresh, perfectly transparent orthoclase is formed all around the original grain. Such new matter also penetrates within the old crystal along its fissures, recementing the separated portions by fine lines of new orthoclase. It also creeps in between the cleavages, especially if they are open enough to serve as solution planes, and by depositing a cement of fresh material it regenerates the old crystal. At the same time while this general enlargement and reconstruction is going on, the muscovite scales and other alteration products tend toward the centre of the old grain. It is not impossible that this apparent greater centralization of these impurities in regenerated grains may be due wholly to the enlargement of the borders and the general restoration of the chemical integrity about the peripheries of the old grain, and that hence the exact *locus* of the individual muscovite scales in the body of the crystal is not changed by the regeneration; but in many cases, it certainly appears to be the fact that such impurities are crowded closer together and generally toward the centre. Such seems to be the case, at any rate, when in the same grain the impurities are gathered in two or three places by reason of some variation in the manner of influx of the fresh matter, instead of remaining, as at first, uniformly scattered throughout the crystal. These features of regeneration are seen in nearly all granites and gneisses. (See Nos. 1278, 1427, 1436, 1728, 1980, 1992, 2229, 2276.)

In general, the new orthoclastic material is perfectly oriented with the old. Indeed, it is probable that, as with quartz, the whole of the old crystal is revamped and undergoes a complete recrystallization, a change which would of course allow if not require the concentration of the inclusions at one or two places, in groups. But it has been noted, in a few instances, that the new feldspathic material is not oriented with the old. One instance (No. 1051) was carefully examined and it was found that the new feldspar had the optic characters of a "deformed orthoclase," *i. e.*, that the positions of the elasticity axes n_g and n_m were the reverse of those in the original grain. In several cases (illustrated by rock No. 1515, and plate V, figure 7) it also appears that this manner of interpenetration by new orthoclase presented a rather spreading microclinic arrangement, and such arrangement only appeared in certain areas in the old grain (Nos. 1992, 2194). The idea that the microline structure is wholly caused by such new intercleavage growths in an old feldspar was rather strengthened when it was observed that the microcline structure itself is uniformly most prevalent in such regenerated rocks (granites, etc)., and that its crystals sometimes grade off into non-microclinic orthoclase.

This "altered" condition of the orthoclases in granites, etc., has sometimes been attributed to decay since the formation of the rock in which they are found, and the microcline structure to unequal strains in orthoclase caused by mountain pressure. As the two facts are frequently concomitant, such decay and such unequal strains have been believed to be complementary and nearly cotemporary.

Whatever may be the causes of such phenomena in other places, we have seen no reason to attribute them to recent decay nor to mountain pressure in the rocks we have examined from the Archean in Minnesota. Indeed, we place them at the opposite end of mineral genesis. The minerals presenting these features are fresh and chemically intact. They had passed through a primordial period of decay, but they are now fresh and pure, and the elements of that earlier decay are rejected by the new crystallization. The following considerations seem to preclude the idea that this alteration is due to recent decay, or even to decay since the present solid condition was acquired by the rocks concerned.

1. No such alteration is known since the Glacial epoch.
2. This alteration is not superficial, but universal and at all depths examined.
3. It is not marginal on the grains, but central.
4. It is not in the midst of decaying rock materials, but in minerals having a fresh and strongly interlocked granitic texture.
5. The rims that extend beyond the old borders are fresh and sometimes even glassy in their transparency.
6. The same distinctions can be seen in some porphyrel which is unquestionably a partially recrystallized clastic containing many large old feldspars, as well as in some graywackes.
7. The other elements, such as hornblende or biotite and muscovite, are wholly fresh. They seem to date from the generation of the new feldspar and quartz.
8. These elements, with sphene and epidote, are evidence of some former period of alteration, and their freshness denotes a later period of recrystallization.
9. Such central "alteration" is not seen in the diabases nor gabbros, nor in the greenstones, nor in the most of the graywackes and conglomerates, but in these rocks the feldspars, when partially decayed, are evenly sprinkled with the products of such change, or are chiefly altered about their margins.

In the "red rock" series a substance occurs abundantly which has frequently been assumed to be orthoclase, but which in some instances is a semi-devitrified acid(?) glass and in others is the result of change of some plagioclastic element. The former is most frequent in the aporhyolites and the latter in the contact rocks of the red series with the diabases (No. 686). In some instances there is left enough of the albite twinning to show that the feldspar, which is perhaps reddened by hematite, is really an altered plagioclase (Nos. 42, 45, 850). Sometimes, apparently, considerable rock masses, belonging normally to the basic series, have been so permeated by the acid elements and stained by hematite that they appear to belong with the red-rock series, and the cause of such an error is attributable to the orthoclastic aspect of the red feldspars, more than to any other feature.

Adularia, a form of orthoclase, occurs at the old Minong mine, on Isle Royale, where it is associated with calcite, forming a crystalline coating on metallic copper and lining geodes, the adularia being of later date than the calcite (No. 583). The origin of this mineral is probably due to solfataric action during the eruptive activity of the Keweenawan.

Oligoclase, andesine, etc. These intermediate lime-soda feldspars have a wide range but not great frequency of occurrence. They have been found in numerous acid and intermediate rocks. Oligoclase favors the granites, quartz-porphyries and syenytes, and the acid metamorphic rocks, but andesine is more allied to the basic series (No. 300). The former is more frequent in the acid mica schists and the latter in hornblendic. They occur in some of the conglomerates, especially those of Keke-quabic lake (Nos. 1061, 1062), and in the esterellyte of that vicinity (Nos. 1094, 1399). Oligoclase is very often associated with orthoclase. Andesine has been found in the clastic greenstones (No. 1367C).

Albite. The pure soda feldspar has been identified but rarely (Nos. 403, 872, 2102 and 2243). Some part of the white feldspar in a coarse pegmatyte (No. 1997) is albite or oligoclase-albite. It is there associated with microcline. In all cases it seems to be a secondary mineral. It takes part in the formation of epidosyte (No. 842).

Labradorite in its broader sense is the prevalent feldspar of the basic igneous rocks, especially of the Keweenawan. Indeed, it may be said that in normal conditions it is the sole plagioclase. When other feldspars have been identified in the diabases or gabbro of the Keweenawan (No. 222) it has been in nearly all instances under circumstances warranting the presumption of endomorphism resulting from contact on the clastics, and this is especially true of the occurrence of andesine or of oligoclase and orthoclase. In several instances the feldspar of the Keweenawan diabases has been identified as bytownite (Nos. 810, 814) or labrador-bytownite, these determinations having been indicated by the extinction angles and not by chemical analyses. In such determinations throughout this work great reliance has been placed on the extinction angles in sections cut perpendicular to the bisectrices as established by Dr. Fouqué of the Collége de France.* An unequivocal occurrence of anorthite in the Keweenawan has been so rare that it produces little or no effect on the proper description of the Keweenawan basic rocks.

*Contribution à l'étude des feldspaths des roches volcaniques. *Bulletin de la Société Française de Minéralogie.* Tome 17, p. 283, 1894.

Aside from the Keweenawan, however, labradorite is comparatively rare in Minnesota. It is found in connection with the rocks intermediate between the gabbro and the greenstone of the Keewatin, *i. e.*, in the muscovadytes, where it is often associated with very unusual companions, but in other parts of the Keewatin it is so modified by decay or regenerated by subsequent new growths, or is rendered so indefinite in its optical characters that it may be said to be practically wanting.

Labradorite in the Keweenawan shows a peculiarity—which is not confined, however, to this mineral—in having not only two dates of generation, *i. e.*, that of the "first consolidation" and that of the second, but different relative dates as to the accompanying minerals. It is sometimes earlier than augite, as in all the ophytes and in some portions of the gabbro, as the latter term has been used, and is sometimes later or cotemporary with augite. The former structure is illustrated by figures 2 and 12 of plate I, rocks Nos. 108 and 820, and the latter by figure 4 of plate I, rock No. 122 and by rock No. 137. It also sometimes occurs that the same rock section shows two dates of labradorite, with respect to the augite associated with it (Nos. 802 and 2064, plate V, figure 6). Labradorite is usually later in origin than olivine, in the basic rocks of the Keweenawan, but there is a large central area of the gabbro mass in which it crystallized earlier than the olivine. This rare structure is illustrated by figure 7 of plate I, rock No. 258, and by figure 1 of plate V, rock No. 1829, and it has been noted in numerous other rocks, viz., Nos. 512, 560, 603, 703, 787, 819, 1275, 1828, 1829, 1842.

In the muscovadytes labradorite sometimes embraces poikilitically the other minerals and sometimes it is in globular small grains embraced in them. The anorthosyte masses of the Keweenawan are composed, so far as observed, of labradorite (Nos. 113, 128, 200A, 223, 637).

Bytownite, for petrological consideration, is to be classed with labradorite, and may exist in the Keweenawan in greater frequency than is known. Sometimes it has been identified distinctly (Nos. 770, 810, 814) and in other cases it seems to be labrador-bytownite (Nos. 128, 258).

Anorthite, which is theoretically a pure lime feldspar, has been but doubtfully recognized in the Keweenawan (Nos. 133, 176, 222, 637). An impure anorthite was discovered in a fragment in clastic greenstone (No. 1367*b*).

Anorthoclase. This mineral, which can be considered the result of a variable combination of the molecules of orthoclase and of albite, has been identified several times in the rocks of the red rock series, especially in the granites (Nos. 1B, 292, 511). It occurs also as a porphyritic constituent in the red aporhyolyte of the "Great Palisades," No. 140(7), and in the associated granophyres at Pigeon point.* The same feldspar has been identified with more or less certainty in the granites of

*W. S. Bayley. The eruptive and sedimentary rocks of Pigeon Point, Minnesota. *Bulletin cix, U. S. Geol. Survey*, p. 52, 1893.

Kekequabic lake (Nos. 551G, 1061, 1399), in the granite of White Iron lake (No. 953) and in the granite quarried at East St. Cloud (No. 835). In all these cases it is so environed, either microscopically or taxonomically, that it appears as the result of contact of basic molten rocks on some acid rocks, and in the aporhyolyte it originated by crystallization from a molten acid magma, itself the result of fusion of acid clastics.

Cordierite, silicate of alumina and magnesia, with a small amount of iron, is one of those colorless secondary minerals which resemble the acid feldspars in affecting the zones of metamorphism and igneous contact. There is no doubt that it has escaped observation in many instances, as it might be taken for feldspar or even for quartz, unless specially examined. It not only occurs in the Animikie when modified by the gabbro to a fine mica schist (Nos. 1708, 2055, 370H), but in the biotitic muscovadyte where it is associated with other magnesian minerals and with quartz and labradorite, as well as much magnetite. In the former case it is plainly divided into vertical sectors (No. 370H) which is not in keeping with the general rule lately stated by Teall,* which requires this feature in cordierite of volcanic rocks rather than in metamorphic. It is evidently frequently of later origin than the most of the minerals of the rocks in which it occurs, as it embraces them in a micropoikilitic manner (No. 1708). In the muscovadyte, *i. e.*, the modified basic clastics of the Keewatin (Nos. 1039, 1042, 1090, 1092), its habit is like that of the other minerals, viz., roundish granular, or granulitic, but it sometimes is wholly surrounded by quartz, by biotite (No. 1042), or by some feldspar. In all cases, therefore, in Minnesota, so far as known, cordierite has resulted from metamorphism.

Muscovite. This term has been applied to a light-colored mica seen in large, sometimes porphyritic, scaly masses (Nos. 923, 2263, 387H, 390H). In this mica silica, alumina and potassa are in greater amounts than in biotite, and magnesia is wanting. It hence affects the alkaline and acid rocks, whether metamorphic or plainly fragmental. In the metamorphic schists (No. 431) it is of late origin and embraces the quartz poikilitically (No. 2061). It is uniformly the product of alteration of alkaline feldspar.

Sericite differs from muscovite only in being in minute scales. It is the basis of the sericite schists, and is very abundant. It is the most conspicuous element in the rejected products of recrystallization of the old feldspars in the metamorphism of clastic debris (Nos. 1278, 2194, 2229) and remains at the centre of the old grains. It has probably been called kaolinic in numerous instances in the microscopical descriptions, although not having the vermicular grouping of the scales of kaolin, and perhaps holding too much of the earthy or alkaline bases for kaolinite.

* J. J. H. Teall. The Natural History of cordierite and its associates. *Proceedings of Geologists' Association*, vol. xvi, Part II, pp. 61-74, 1899.

Epidote. This is a very common but not very abundant mineral. Its earliest appearance is as small grains or groups of grains in the Lower Keewatin greenstones, where it is plainly the result of alteration of the feldspars in presence of iron. It is essentially a silicate of alumina, lime and iron. From this primary source (and by analogous production in later rocks) it is disseminated amongst the later rocks that are dependent on the oldest basic crust for their essential characters. It is also common in scattered grains in the more acid of the schists of the Archean, which also probably received the elements of which it is composed from the basic rocks of the earlier Archean.

It is a rather common mineral in the Archean granites, quartz-porphyries (?) (No. 914), and gneisses (Nos. 435, 994, 995), and especially in the "intermediate" series represented by the diorytes and by the amphibolytes (Nos. 401, 403). It here forms isolated crystalline grains, and its date appears to be as early as that of any of the constituent minerals of those rocks. Whether it was incorporated as epidote into the original clastic materials of which these rocks are believed to be primarily composed, or has originated through metamorphic recrystallization, it is difficult to affirm with present data, but from its general absence from the graywackes and other non-crystalline detritals of the Archean (see, however, No. 488), it appears to have been in the main the product of recrystallization under the action of metamorphic forces. It is therefore probable that, in the Archean, epidote is one of the distinctive metamorphic minerals.

It does not, however, depend wholly on metamorphism, for it is found in the Keweenawan basic rocks, where it seems to have been produced by ordinary weathing, or by the action of heated solutions on the lavas during the period of cooling, after congealation (Nos. 567, 569, 697).

In a single instance (No. 842) has it been found abundant enough to control the nomenclature of the rock (epidosyte). It is there associated with albite.

Zoisite. Zoisite is allied to epidote, but is practically free from iron, and it is probably less the product of metamorphism. It is rather the direct product of simple feldspathic alteration produced by solfataric exhalations or by heated solutions (Nos. 868, 872, 922, 1802). Accompanied by more or less of chlorite, mica and new feldspars, it constitutes very largely the impurities that pass under the general name saussurite. A saussuritized feldspar may be, and is frequently, embraced in the detrital rocks. Under such conditions, on the advent of metamorphism zoisite seems to maintain its identity in the resultant schist or dioryte (Nos. 861, 881).

Zeolites, of which a considerable number of species have been identified, are likewise the result of alteration of eruptive basic rocks or of their debris. The index may be consulted for reference to the important discussions.

Tourmaline, which indicates the near action of volcanoes, containing boracic acid and sometimes lithia, with varying amounts of magnesia, soda and iron, is primarily a silicate of alumina. It has been found in microscopic crystals in the greenstones and in Archean schists, as follows: Nos. 395 in clay slate, 473 in graywacke, 737 in conglomerate, and 2162 in a quartz schist. It cuts the quartz in a vein in No. 352. It is in syenyte in No. 993, in quartz-porphyry in No. 2237, and in gabbro in No. 773. It occurs in the Pokegama quartzyte, base of the Animikie, at Pokegama falls, No. 1525(a), and in the quartzyte and black slate of the Animikie in No. 1852.

Apatite. The occurrence of this mineral in greater abundance along the zone of contact of the Keweenawan basic eruptives on the clastics than elsewhere in the state, so far as known, is indicative of the causes that have promoted its origin. In these situations it is always idiomorphic. It is sometimes surrounded by hornblende and sometimes by orthoclase or by quartz, and these are all secondary minerals in the broader sense of that term, as already defined, and result from the transference of the acid elements into the basic rock. Apatite resembles sphene in the vigor with which it asserts its crystalline boundaries. Wadsworth has contended that apatite in these conditions is secondary, and the writer is inclined to indorse that view, but from different considerations. It is customary to place apatite amongst the earliest of the phenocrysts to appear in a magma when cooling. This is probably true of acid magmas (Nos. 858, 1025A, 1032, 1061, 1094, 2215), to which the larger crystals of magmatic apatite appertain, but it has but little application to basic magmas, because apatite is generally not found in them except at contact zones, where it has apparently been produced by endomorphism from the older rocks (Nos. 1B, 5, 459, 512, 531, 595, 540, 789, 1684, 1685A, 1802). When it is seen in the Archean granite (No. 368G) or dioryte in large crystals, it is likewise idiomorphic, and appears to have been one of the earliest crystals to form from the acid magma (Nos. 425, 805, 339B). Such crystals are, however, nearly always much worn, or "corroded" at the angles, and they may have been of still earlier date, *i. e.*, they may have been grains of clastic origin deposited in the debris from whose recrystallization the granite is supposed to have been formed. Such clastic apatite occurs in rocks Nos. 311, 2262, 366H. Apatite occurs sometimes in diabase (Nos. 221, 1076).

Barite is known to occur only in some veins that cut the quartzytes and slates of Pigeon point (Nos. 272, 288A and 288B), where it constitutes a large percentage of the vein matter.

Calcite, besides forming the chief constituent in many veins (Nos. 272, 423) and the filling of much amygdaloid, exists in microscopic particles in most of the clastic greenstones (Nos. 1015, 1018, 1068), in the graywackes (Nos. 473, 494), in the quartz-porphyries, so called (Nos. 387, 376), in the greenish conglomerates (Nos. 874, 908, 1070), in much of the mica schist (No. 422), in many diorytes (Nos. 424, 731, 1410, 1318), and occasionally in granite (Nos. 730, 1100, 2263), and rarely in gabbro (No. 1802).

Calcite shares with quartz the distinction of existing in all rocks except the unmodified original massive greenstones and the similar basic igneous rocks of the Keweenawan. It never, however, forms crystals of perfect form—except in cavities where it has room to develop without contact with other crystals (No. 60A)—but it is minutely disseminated widely where it can be detected only by the microscope.

Siderite. The earliest known appearance of siderite is in the quartz-porphyries of the Archean (Nos. 426, 428) and in the jaspilytes (Nos. 385, 388, 903, 907, 1565). It is also a frequent minor ingredient in nearly all the associated rocks of the Keewatin, whether of the Lower or Upper (Nos. 319, 326, 389, 473, 747, 910, 911, 2266, 398). It appears uniformly as perfect, or approximately perfect, crystalline minute rhombs, and it is not preferably associated with any of the other minerals except hematite, with which it has an intimate connection. Sometimes these rhombs are aggregated in groups (No. 903), in which case they are more correctly styled grains, and exhibit that globular form and small dimension which is characteristic of many minerals in an incipient state of crystallization in metamorphic rocks. When the crystallization goes further, larger rhombs appear, and these larger crystals are seen to surround one or several of the small globules, usually with different orientations. Sometimes the whole rhomb seems to be made up of an aggregation of minute siderite globules, but usually (as in No. 907) there are three or four distinctly outlined, clustered or isolated, round which the darkened border due to the high refractive index comes out markedly on lowering the condensing lens. These globules as a rule do not break the borders of the rhombs, which are straight and extinguish simultaneously, but they lie somewhat away from the borders, not having exactly the same orientation as the borders.

These minute rhombs are also secondary to the minutely granular quartz which usually, in the jaspilytes, constitutes the most of the rock. These granular masses not only displace the quartz so as to make sometimes a spotted rock, of which its quartz grains are of about the same size, but these patches surround and embrace the quartz grains, and quartz grains are also to be seen, occasionally, in the midst of the isolated rhombs. Indeed, the siderite acts the rôle of a poikilitic mineral, embracing the quartz. This is not conspicuously the case, but usually the siderite is independent of the quartz. Yet it is so frequently seen that it is plain that the siderite was developed later than the quartz, or was nearly cotemporary with it. These siderite globules are easily distinguished from the quartz grains that lie within the siderite by the use of the Becke white line, and by the marginal lines of color which surround the included quartzes, due to the high double refraction of the adjacent edges of the siderite, both of which are absent from the siderite globules when quartz is not adjacent. It is owing to their globular composite structure that these rhombs seldom give an interference figure, however cut by the section.

In some of the best sections of jaspilyte that have been examined (Nos. 903, 907), all the iron ores are present, the magnetite, pyrite and siderite in somewhat coarse crystals, and the hematite in minutely fine particles disseminated amongst the finest quartz. If any distinction as to priority of origin can be drawn from this section, it is in favor of hematite, since it is distinctly embraced in the siderite as nuclei of the fine rhombs of that mineral (No. 1565). The magnetite is in distinct octahedra and the pyrite in cubes. These must be later than the hematite, which is in dust-like scales and powdery aggregates distributed amongst the fine jaspilitic quartz, and appears to be the cotemporary of it in origin and like it in manner of deposit. The hematite and quartz are non-differentiated by independent coarser crystallizations. The pyrite, magnetite and siderite are in large (microscopic) crystals and crystalline aggregates.

As to the origin of this early siderite it is to be attributed to some source which allows for the access of carbonic acid to the iron which was taken up by its formation. If the jaspilytes were formed in the bottom of the Archean ocean by chemical precipitation,* carbonic acid may have been derived from the atmosphere primarily, and secondarily from the ocean. It will be seen, however, below, that it is not improbable that this siderite originated in the manner similar to that which permeates the iron-bearing rocks of the Mesabi Iron range, and that those rocks were not the product of oceanic chemical precipitation.

The mineralogical environments and the petrographic structures of the siderite of the Mesabi Iron range are, in general, so much like those of the siderite of the Vermilion range that it seems necessary, in the light of the detailed examination presented in Part II, to consider them one in origin though differing widely as to date. The greater recentness of the Taconic ores seems to have been favorable for the preservation of some of those bonds of alliance with attendant conditions by which their origin and history can be traced out, but which, in the Archean ores, are so far destroyed that the relations of cause and effect cannot be detected. It is by reason of the microscopical and other examinations of a wide series of iron-bearing rocks of the Mesabi range, extending from Gunflint lake to the Mississippi river, that the writer has been led to regard the origin of those rocks very differently from the view formerly entertained by him, and quite different from the opinions presented by other geologists. At this place, however, it is designed to discuss only the sider-

*Bulletin vi of the Minnesota Geological Survey.

itic condition of the ore of the Mesabi Iron range. The general question of the origin of the rocks as such will find place in the next succeeding chapter.

The writer finds that in certain parts of the Mesabi Iron range the iron of the iron-bearing member is largely sideritic. This condition prevails about Gunflint lake and continues to a greater or less extent westward as far as to the vicinity of the Mallmann mine in T. 60-13 W. It gradually changes, and the oxides of iron are substituted for the prevalent carbonate. The change is not complete, for some carbonate is found at the western end of the range (No. 1588) in the same manner that the oxides also are found about Gunflint lake. With this exception, and with the further exception that the iron ingredient is more abundant toward the west, the iron-bearing member is, itself, essentially a uniform terrane. There is this further difference, viz.: Toward the west the Pokegama quartzyte generally separates the iron-bearing rocks from the Archean, while toward the east, *i. e.*, at Gunflint lake, the iron-bearing member lies sometimes directly on the Archean, and no representative of the Pokegama quartzyte has ever been seen there *in situ*. It appears, therefore, that such a variation from siderite to hematite must be due to some variation in the nature of the conditions attending the formation of the rock itself, such that oxide of iron was formed more abundantly in one part of the state, while in the same terrane, in another part, a carbonate of iron prevailed.

This carbonate of iron about Gunflint lake makes small rock masses, and it has been called sometimes limestone (Nos. 312 and 1310). One of the first samples collected (No. 312) is represented by the photograph, natural size, seen in plate VI. It here embraces many angular masses of flint, or chert, which the writer regards as devitrified glass of volcanic origin, originally of basic composition, but now composed largely of quartz. Such flint is abundant about Gunflint lake, not only as fragments in this siderite, but in horizontal thin beds that are intimately interstratified with some Animikie "slate," and taconyte (Nos. 1276, 1277). In other words, the flint, the volcanic glass and the taconyte are intimately associated, and their elements are variously involved in the siderite (No. 1289).

Again, the sideritic rock (plate VI) exhibits sometimes a parallel, streamed (or sedimentary?) structure seen in No. 1 of the plate referred to, and in No. 1588, and in other parts this structure is replaced by a more confused sideritic rock. The siliceous flinty pieces are placed in all positions in this confused part of the mass, but in the streamed parts they tend to parallelism with the direction of the streaming. This structure may be due to an original lava under flow, carrying many pieces of obsidian previously hardened.

That the sideritic rock was once a lava and is simply changed by becoming ferrated and carbonated or is a product of leeching from it, is indicated by a series of observations, accompanied by microscopical study of thin sections, made at a point about one mile west of Gunflint lake (S. E. ¼ sec. 24, T. 65-4), and of the taconitic structures seen about Gunflint lake. The former locality is represented by the following sketch. The rock seen in the isolated hill at the right consists of sideritic

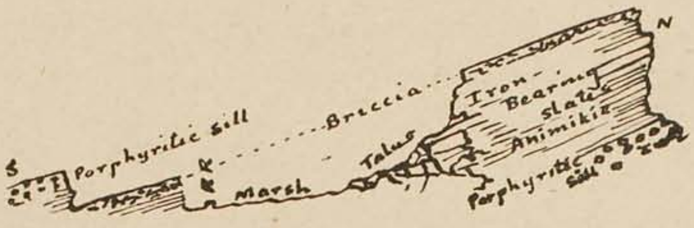

FIG. 54. PORTION OF THE ANIMIKIE CONTAINING IRON.
S. E. ¼ sec. 24, T. 65-4, near Gunflint lake.

slates, more or less magnetited, constituting the iron-bearing member of the Animikie, passing upward into a flinty breccia of iron-bearing beds. This breccia descends with the dip to the railroad track (No. 1897), where it also is underlain by unbrecciated slates. "It is from five to six feet thick and is composed of Animikie slate and quartzyte, some of the pieces being over two feet long." The cement of this breccia is a greenish fibrous matter, largely actinolitic and also sideritic, and weathers to a rusty surface in the same manner as the sideritic rock No. 312. Indeed it cannot be questioned that the breccia No. 312 (plate VI) was derived from a stratum in or near the bottom of the Animikie, as represented by the above figure. In making an examination of the cement of this breccia, which cement grades into the iron-bearing (sideritic) member of the Animikie, it was found to assume the characters of an igneous rock (Nos. 2052 and 2053), in which, while siderite still exists, yet cummingtonite and devitrified glass abound. As a lava it seems to have given birth on cooling to many nodules of more crystalline rock matter which, on the weathering away of the intervening matrix, stand out on the surface as black balls in a manner like the balls in a surface trap seen on Grand Portage island (No. 544). These balls now consist almost wholly of cummingtonite or some other amphibole, and the intervening matrix which surrounds the balls is a partly devitrified basic lava or chloritic zirkelyte.

It appears, further, that while the ores, siderite and magnetite, are found in all parts of this breccia, the carbonate is abundant in the matrix of the breccia and the oxide in the fine or flinty portions which form the angular pieces in the breccia. In other words, the carbonate formed later than the oxide, and in such free access of carbonic acid that, in some cases, nearly the whole rock is composed of siderite. There must have been also a free leeching process possible in the concentration of the elements of the lava to siderite, in order to have removed the silica and its bases, while in the concentration to the usual ingredients of a devitrified basic apobsidian the environment in some way restricted the free access of carbonic acid.

The writer cannot at present explain this curious difference in the transformation from basic lava, but he has surmised that some of the lava may have congealed on a land surface and some beneath the water of the ocean, and that the flow breccia(?), in which the matrix is largely siderite, may have been originally a surface lava. (Compare No. 1298.)

Further, if the igneous rock was poured out on a land surface, it is apparent not only that conditions would be favorable for the local formation of fresh-water pools and sometimes of small lakes, but also that, in case of organic matter flourishing in such pools, there would be a deposition of carbonate of iron which might have enclosed, in the manner represented by plate VI, much of the glassy debris of the lava sheet. On this hypothesis the mass of the lava proper is not changed to siderite, but the chilled upper surface is devitrified and its debris is preserved with its characteristic features; about the borders of such lakes, and along the sea beach, much volcanic glass sand must have mingled with the carbonate deposit, and sometimes replaced it entirely.

The further consideration of this presumed igneous origin of the iron-bearing member of the Animikie is deferred till the discussion of the iron ores and the taconyte. It is intended by the foregoing to call attention to the practically simultaneous origin of the oxide and the carbonate of iron in the iron-bearing rocks of the Mesabi range, and to the microscopical priority of the oxide. Genetically neither depends on the other, but they had a prior common cause of existence, and took different chemical conditions because of differing environments. This accords fully with the descriptions above of the relations between these minerals in the Vermilion range. That the ore of the Vermilion range was not derived from siderite is proven by rock No. 1572, since that mineral here not only surrounds and embraces the hematite, but forms veins that intersect the red jaspilyte in all directions, one vein being a quarter of an inch wide.

Dolomite, which is a common amorphous ingredient in the limestones in the southern part of the state, has been found to constitute a dolomyte in one instance (No. 824), where its crystalline form is finely exhibited by nearly every grain. It is the upper portion of the matrix of the upper conglomerate at Taylor's Falls, belonging to the Upper Cambrian.

(2) The Colored Minerals—Augite.

This is the most ubiquitous of the ferromagnesian minerals, especially in the basic igneous rocks. Under this designation may be embraced, in a general way, all the pyroxene which has been included in the foregoing microscopical descriptions, although in a few instances some varieties have been specially noted. These will be mentioned below.

In the oldest rocks (the Kawishiwin igneous rocks) augite is found with its optical characters usually destroyed, but its ophitic relation to the associated feldspars still preserved by the resultant uralite (Nos. 1011, 1078, 1758, 1759, 1760). In the Kawishiwin clastic greenstones it is uniformly converted to some form of hornblende (Nos. 356, 997, 1003, 1014, 1071), except where for some favorable conditions it has been partly preserved as augite. In the Upper Keewatin, about Kekequabic lake, where it is markedly affected by ægyrine characters, whether in the green schist or in the granite and porphyry (Nos. 1399, 1767) it is sometimes well preserved (Nos. 1094, 866) and is sometimes partly converted into hornblende (Nos. 1400, 1047, 1060) or disseminated in the alteration form of actinolite spicules throughout the schist (Nos. 1419, 1421). In most places in the clastic greenstones of the Upper Keewatin it is wholly lost by alteration to hornblende and to chlorite (Nos. 1345, 1788, 1799) and this is universally true of the acid clastics which frequently embrace hornblende that may be supposed to have been derived wholly or partly from augite.

There are some hornblendic intrusives in the Keewatin which contain phenocrysts that afford curious and characteristic phenomena, presenting alliances with camptonyte (Nos. 872, 877, 915, 1318, 1786). Such are found about Vermilion lake and at Ely (No. 1786) and indicate that even in such conditions the original augite grain, or fragment, has been through such mechanical and chemical stress that it has taken on the hornblendic crystalline form, but has retained an impress of its prior state. Such ancient augitic areas seen in hornblendes are indicated by the greater absorption which appears at the centres of the hornblendes, or which spread irregularly through them (Nos. 872, 1047, 1786). This feature appears not only in the distinct dikes at Vermilion lake and at Ely, but also in much of the intrusive, recrystallized rocks of Kekequabic and Snowbank lakes. Such alteration and intrusion, when seen in the Upper Keewatin, was probably pre-Animikie.

In the Keweenawan augite is a more abundant mineral than in the Archean, owing probably to later origin and to less of mountain-making vicissitude, as well as to the preponderance of basic igneous rock in that formation. In the Keweenawan also, as a rule, it is nearly unchanged. Its clearness and purity are evinced in every thin section taken from such portions of the interior of the rock where it has received only the normal influences. In other words, time has had no noticeable effect, denoting metasomatic alteration (Nos. 639, 820, 1137). It is only where the Keweenawan rocks containing augite have experienced an unusual history, either before or after consolidation, and usually prior to final cooling, that augite has been altered. It is then sometimes changed to chlorite, or magnetite and chlorite, or its elements are so scattered in the production of new secondary minerals and mingled with those from other sources that they cannot be traced to their present resting places. In such cases the causes of these alterations, inherent in the accidental environment, are easy to see. The chief of these is plainly solfataric activity, penetrating and attacking the lava during the cooling period. Its purveyors were hot solutions and gases, the chief of the latter being steam. Secondly should be mentioned endomorphism from the contacts on the surrounding acid rocks. These agents were cotemporary and complementary. They had their greatest effect where the augites are wholly altered to hornblende (Nos. 554, 1848, 1849) and where the plagioclases are reddened. This is a combination which is sometimes accompanied by widespread interfusion and mingling of the basic magma with extensive areas of the acid, the two becoming completely and mutually mingled so as to produce igneous rocks of intermediate type in the Keweenawan (Nos. 5, 648, 650, 674, 675).

There are also some petrographical peculiarities appertaining to augite examined in the Keweenawan and in the muscovadytes:

(1) Its optic angle is sometimes very small, being apparently not over 5°, but varying to 45° (Nos. 126, 223, 291, 297, 1828, 2001, 178E), and it has been noted that this is accompanied in the same rock by the ophitic relation of olivine to plagioclase (No. 1828).

(2) It appears sometimes to have two generations in the same rock, *i. e.*, it is both granular and earlier than, or cotemporary with, the generation of the plagioclases, and is ophitic in its relation to the plagioclases (Nos. 89, 133, 222, 228, 229, 515, 517, 615, 820, 2064). In other cases it is wholly granular (No. 122) or wholly ophitic (Nos. 53, 106, 108, 625). The ophitic structure is uniformly the latest to form, at least it is later than the granular when both exist in the same rock (Nos. 515 and 517). The granular condition prevails in the muscovadytes and in the gabbros proper, but it is not confined to the coarser grained rocks. It appears in the finest of the diabases (No. 654), even in zirkelyte or glassy diabase (Nos. 540, 541). In No. 547 augite is porphyritic in a glassy base. In the muscovadyte it graduates apparently into the "globular structure" (Nos. 1334, 1347) described below. It is plain that the granular structure cannot, of itself, be said to be characteristic of gabbro, nor the ophitic of diabase. On the other hand, this intimate association of the granular and the ophitic structures in the same rock destroys the usefulness of this distinction as a character on which to base nomenclature, and points to the conclusion that diabase and gabbro cannot be dissociated on a genetic basis.

(3) It has been customary to account for these two structures of augite on the assumption that the granular was formed under a state of flow in the rock when the crystallizing points were continually separated, and the ophitic after the rock came to rest. There are, however, some facts that can hardly be explained in that way. (a) The ophitic structure prevails in the surface lavas and dike rocks, which are admit-

tedly the most likely to have been affected by such action, since they were in a condition of flow as long as possible (Nos. 7C, 7D, 23, 38, 206), and are wholly ophitic. (b) The granular prevails in the deep-seated, such as the granular gabbros, which must have been least subject to flow (Nos. 1784, 857G). (c) The granular is found in the muscovadytes which have never been in a condition of flow, but stand in their original, often bedded, relations to each other, preserving their original Archean dip (Nos. 667, 698, 767, 857G, 857aG). (d) When both structures exist in the same rock, the earlier augites are sometimes embraced poikilitically in the later (Nos. 515, 2064). It would hence appear that the granular condition is not dependent on the commencement of cooling. (e) The earlier augite is apt to be diallagic (Nos. 291, 292). This indicates that diallage is not a product of late generation, but a feature of the deeper portions of the rock. (f) The granular augites are about equigranular. If the ophitic augites resulted from crystallization after a state of rest was acquired, the question arises, Why did the earlier augites wholly cease growth, and, while maintaining their existence, refuse to serve as nuclei for the fresh later augites? *i. e.*, why did they not all simultaneously resume the augitic growth, and why did certain new larger crystals of the same mineral start an independent development?

(4) Augite is frequently seen in a globular, or infantile, condition (Nos. 1092, 1334, 1347). This is usually the case in much of the rock muscovadyte (or noryte) and in the gneissic muscovadyte which has resulted from the recrystallization of basic clastic rocks of the Keewatin. Where the original clastic material was more acid, diopside is more common.

(5) The augite of the granite of Kekequabic lake, and in part at least of that of Snowbank lake, is so supplied with soda that it may be styled ægyrine-augite. It is fully described in connection with Nos. 1094, 1105, 1106, 1399.

Diopside. In several instances the pyroxene examined has exhibited characters of diopside, *i. e.*, has a cleavage parallel to 010, but in all such cases it is in circumstances that have indicated the secondary origin of the pyroxene. In No. 132A it is fresh and green, being in one of the augite granites. In these granites it descends (as in No. 643) to globular dimensions and is scattered in that form through the altered feldspars. Without having made careful examination in the "augite granites" of the Keweenewan, it is here only suggested that it is probable that this form of pyroxene prevails in these rocks. (Compare No. 1805).

It has also been identified in some of the spherulitic and micro-pegmatitic secondary growths at the contact zones of the Keweenawan (Nos. 132A, 667 ?), where it forms long, somewhat acicular crystals which pierce the altered feldspathic elements with great freedom and in a conspicuous manner. In the diabases where modified by such contacts the same petrographic character has been noted in the pyroxene (No. 137).

Diallage. The diallagic cleavage of augite is common in the diabase and in the gabbro of the Keweenawan, as well as in the muscovadyte. In the diabase it is seen in Nos. 115, 222, 1605, 1287. In the gabbros in Nos. 1C, 698, 985, 1136, 1137, 1287, 1678, 1749. In the muscovadyte it is conspicuous in Nos. 122, 1287, 2199, 2201. Diallage has not been observed in the Archean rocks.

From all that has been observed, the diallagic characters of augite appear to have an early date. Far from being due to secondary causes, and hence a secondary feature of the pyroxenes of the Keweenawan, the characteristic lamellation appears rather to be one of its primordial characters. It is most frequently seen in those pyroxenes that antedated, or were coeval with, the plagioclase and olivine (Nos. 1C, 1287). It is in the muscovadyte that it is intertwined in a lamellar succession with enstatite (Nos. 1340, 2199) and with hypersthene (No. 2202).

There is, however, a diallagic structure which results from late alteration of augite, and in some instances it has been accepted by petrographers as the true structure of diallage (No. 300), but it should be kept distinct. There is no doubt that this confusion of two structures under one name has been the cause of much difference of opinion as to the nature, origin and date of the mineral diallage. That diallagic lamellation which is of later date and is attributable to natural decay from weathering or other influences is fine and fibrous, is parallel to the base of the augite crystal, and it destroys the orientation of the augite which is affected by it. It is described and illustrated by Wadsworth in Bulletin ii of the Minnesota Survey, plate VII, figure 1, and page 80. But that lamellation parallel to 100, which is the structure that characterizes the oldest diallage of the gabbro and of the muscovadyte, does not destroy the orientation of the augite. Non-diallagic, ophitic augite often exists in the same rock with true diallage (No. 222), and true diallage is sometimes also ophitic (Nos. 115, 847G).

There seems to be a fundamental difference between diallage and diopside, viz.: The true diallagic lamellation 100 perpendicular to the optic plane is original and primary, and exists in the gabbro the result of refusion of the (usually) clastic greenstones, but that of diopside (010) parallel to the optic plane is a character of the pyroxene developed later, as in gneiss and crystalline schists, as well as in some of the so-called augite granites, both of the Archean and of the Keweenawan.

Hypersthene. This is the most common of the orthorhombic pyroxenes. It is, however, practically restricted to the muscovadyte series, *i. e.*, to the zone involving the transition from the old Keewatin clastics to the gabbro of the Keweenawan, whether considered genetically or geographically; but it also continues slightly beyond the transition, on the gabbro side of that zone, and thus gives name to a rare rock called "hypersthene gabbro" (Nos. 1037, 692, 1710, 178E). It here exists in all stages of development, from the initial "globular" form (Nos. 1042, 1037, 1710, 1784) to crystals of large size (Nos. 692, 1042, 1037, 1362, 1364, 1712, 2197, 397(a)H), which frequently embrace all the other minerals poikilitically (No. 618). In the globular state it is found entirely surrounded by biotite in No. 1042, by hypersthene in No. 1037, by magnetite in No. 1040, by feldspar in No. 1784.

Enstatite and bronzite. The former has been noted in muscovadyte (Nos. 705, 983), but the latter has only doubtfully been identified.

Bastite, which is perhaps an alteration product of enstatite or bronzite, at least a secondary mineral, was once noted in a hypersthene gabbro (No. 1710). This is at or near a muscovadyte horizon, noted for the novelty and the multiplicity of its mineral associations, and hence it is reasonable to suppose that it is another of the curious creations of this zone of metamorphism, rather than an alteration product after another mineral.

Hornblende. Among the colored minerals hornblende to a notable extent plays the rôle of quartz among the white ones. It is easily formed, either under ordinary decay of some of the other earlier minerals, or under metamorphism. It is hence present, in some of its varieties, in nearly all rocks that have been examined. The green color of all the greenstones is almost wholly due to ordinary hornblende. It is abundant in all the crystalline schists, even in the mica schists. There is scarcely a granite that is free from it, nor a syenyte, while in all the diorytes it is mainly hornblende that gives the dark, or spotted-dark, color to the outward aspect, sharing it only with some epidote or a monoclinic pyroxene, which latter is usually diopside. It passes through all the stages of development from the globular to the idiomorphic and porphyritic. It is necessary here to mention only some of the most important of the features it presents in Minnesota and to enumerate the varieties that have been identified.

Globular stage of hornblende. Beginning with the earliest recognizable condition in which hornblende has been seen, the globular forms which are mentioned in Nos. 1345, 2104, 2264, 19H, are fair illustrations. It here occurs in incipient granite, resulting from the metamorphism of a clastic debris, in a sphene crystal, likewise formed in the regeneration of a more basic debris and in a muscovadyte which has an alliance with dioryte in the abundance of hornblende which it contains. In the last the globular composite structure of some of the larger hornblendes is still evident in the patchy coloration between crossed nicols, and in the varied shades of green which fleck them when rotated over a single nicol. In the main hornblende has so strong a crystalline independence that the initial globular grains are perfectly arranged in uniform orientation, thus building up the prismatic columns into which hornblende is cut by its cleavages, and it is only in rare instances, such as seen in No. 1345, that the individual globules retain any distinguishing form or coloration. Of all the rocks this feature is most common in muscovadyte.

Hornblende fringes. That hornblende in all its varieties is invariably the result of some secondary forces which have changed other minerals, usually augite, into hornblende, is abundantly shown in the details of the foregoing descriptions. The "porphyritic" hornblendes are simply developed fragments or crystals of augite. This is true not only in some of the green schists, as those seen about the western confines of Long lake (Nos. 2104, 2125), about Fall lake (No. 139W) and in the region of Kekequabic lake (Nos. 1047, 1049), each of which contain other evidences of their clastic origin, but even in the more massive bosses of "hornblende porphyry," and in the narrow (camptonyte?) dikes, seen at Ely and at Stuntz island (Nos. 872, 877, 1786), which are intrusive in the Keewatin. The most clear instance of the conversion of augite to hornblende was seen in a Keweenawan diabase (No. 1847). Here the hornblendic product forms a "fringe" surrounding the augite at its extremities and having separate orientation. This enlargement in other cases is converted to an encroachment, and gradually the whole augite grain is converted to hornblende (No. 872), there being left occasionally only a small remnant, or several globular remnants near the centre (No. 1060), to show the original augitic nature of the grain. This graduated series of changes shows that the "fringe" is the first to form, and that the latest hornblendic molecule was that which replaced the last augitic molecule. That is, it is evident that the hornblendic fringes are not "frayed ends" of hornblende due to dynamic action, as supposed by Williams, nor yet "enlargements" of original hornblende crystals, as suggested by Van Hise, but are the oldest parts of the hornblende grains to which they belong. The outline of the original augite is sometimes preserved by a patch of irregular shape occupying the central portion, which has greater absorption than that which surrounds it, and also between crossed nicols gives a different color of double refraction (Nos. 1047, 139W, 15H). In many, and probably in most, cases, the augitic characters are wholly obliterated and hornblende appears to be an "original" mineral, due to the profound transformation which the entire rock mass has experienced, as in dioryte.

"Original" hornblende. Some hornblendes, in massive rocks, especially those about Epsilon lake, have the aspect of being "original," *i. e.*, that they formed in a molten magma on consolidation. These are Nos. 751, 792G–797G. Some of these have been carefully re-examined, with the following results:

No. 751. So far as can be seen the hornblendes are original.
No. 792G. Has distinct augite remnants within the hornblende.
No. 793G. Shows some central nuclei or remnants, but not of augite.
No. 793aG. Original, so far as can be seen, but with two or three central nuclei, though not of augite.
No. 794G. Original, so far as can be seen; indistinct nuclei, as in No. 793aG.

No. 794aG. Hornblende lost by decay, either chloritized or magnetited.
No. 794bG. Clastic rock, probably tuff; fragments angular, embracing some quartz; no hornblende.
No. 795G. Distinct augite remnants. Hornblende is green.
No. 796G. Much augite remaining as grains in the hornblendes.
No. 797G. Some hornblendes are apparently original, but some have central nuclei not of augite; others are wholly chloritized except at the centre, where are apparently augitic grouped grains, which grains appear to be in part epidote.

The central grains not augite (above) are largely leucoxene, but embrace, apparently, some feldspar and and perhaps some chlorite, while the general hornblendic orientation runs through them, causing imperfect extinction.

It seems likely, therefore, from the occasional existence of augite remnants in these hornblendes, that they are modified conditions of augite. There is no doubt that this rock acts the part of an igneous intrusive, in the same manner as the granite and massive porphyry of Kekequabic lake, and in consonance with that fact the hornblendes appear almost entirely "original," in the usual petrographical sense. In the broad sense, however, that has been indicated (page 940), they are in a secondary rock, and are not original. They are to be considered original only in the sense that quartz and orthoclase are original in granite.

So far as the writer has observed, hornblende appears in the Archean only as a result of alteration of augite or some other minerals under conditions of profound metamorphism.

The varying amounts of alumina and of iron present and available under the conditions that promote such alteration seem to be the prime cause of the different varieties of hornblende that have been noted. *Brown hornblende* is a frequent accompaniment of the gabbro rocks where they carry notable amounts of magnetite, and especially where the gabbro is shading off to muscovadyte (Nos. 703, 1288, 1292, 1711).

Cummingtonite. This name is preferred, on the authority of Hintze,* who, on account of chemical composition, has assigned that mineral, which in Michigan is apparently the analogue of that found in Minnesota, to this species. The mineral here referred to was named actinolite by the geologists of Michigan and Wisconsin, and the rocks to which it gives character were for several years known as actinolite schists, or actinolite-magnetite schists. Subsequently, after the more minute examination and analysis by Lane and Sharpless,† they were known for several years as grünerite schists. This mineral is known microscopically, amongst the amphiboles, for its multiple, narrow twinning, its high double refraction and its fresh, light-colored appearance. It is common on the Mesabi Iron range in connection with the iron-bearing member of the Animikie (Nos. 437, 766, 976, 1365), where the rocks have been somewhat metamorphosed by proximity to the gabbro revolution. It has also been seen several times in the highly metamorphic iron ores of the muscovadyte zone (No. 397(a)H) and occasionally elsewhere (Nos. 1365, 1710).

**Handbuch der Mineralogie*, p. 1230.
†*American Journal of Science*, vol. xlii, p. 505, 1891.

Actinolite, however, of all the fibrous, or fibro-lamellar amphiboles, is most common. It is very abundant in all the green schists, and especially in the green schists about Kekequabic lake. It is probably this mineral that prevails in all the green, altered, basic clastics of the Keewatin, where it has frequently been passed under the simple designation "hornblende."

Pargasite differs optically from the other hornblendes in having n_g for its acute bisectrix (Nos. 1043, 1049). It is probably more common than has been observed, especially about Kekequabic lake, where it occurs in the green tuffs of the region, resulting, as already stated, from alteration of a soda-bearing augite. These hornblendes have not been analyzed, but it is very probable that they would show a small percentage of soda.

Tremolite has been named occasionally, but its optic characters are so similar to those of actinolite that this distinction must be considered as provisional (Nos. 18A, 1137, 1453).

Uralite is the name that has been applied sometimes to a hornblende whose dependence on augite as its source is very evident, sometimes in the preservation of the original ophitic relation of the augite (Nos. 1386, 2255, 2258).

Biotite. There seems to be an easy gradation in optic characters as well as in chemical composition between muscovite and biotite. The alteration of the feldspars is the prime source of both. When such alteration is in the presence of ferromagnesian minerals likewise undergoing change, the mica partakes of the iron and magnesia, thus affording biotite. A simple decay of the feldspars would hardly produce these results, but it must be understood that some agent is acting to promote recrystallization. Such force may be heat, or pressure, or both, accompanied by moisture, and the process may be slow or rapid. Without such forced recombinations the soluble elements of the feldspars would be removed entirely, under ordinary decay, and the result would probably be a pure kaolin (Nos. 1449, 1700, 1701, 1704).

There are, moreover, instances in the igneous rocks (gabbro) in which biotite appears to have been one of the original minerals (Nos. 291, 954).

Muscovite and biotite, often in large crystals, are hence found widely in the granites, diorytes and syenytes that have resulted from the recrystallization of Archean debris. In a strictly petrographical sense they are here original minerals, but they are secondary in the broader sense that they have resulted from the decay of earlier less stable mineral compounds, and have recrystallized under the stress of metamorphic forces.

Biotite occurs porphyritically in a kersantyte which acts as an intrusive in the vicinity of Moose lake (Nos. 2158, 2261).

Chlorite. Including under this term all the chlorites that have been observed (clinochlore, pennine, strigovite, thuringite, ripidolite, delessite), the general remark may be true that they result from the same sort of alteration as mentioned under biotite, but in the process of formation took also water into crystallization. Their alkaline base varies much, embracing also sometimes a notable amount of protoxide of iron.

As the microscopic characters of muscovite and biotite are not always distinctive, so the chlorites fade also into biotite. Chlorite sometimes replaces muscovite or biotite (Nos. 2265, 2277), one lamella after another, in whole or in part, in the same way that biotite is intimately associated with muscovite. Indeed, there seems to be an easy gradation from one end of the series of these foliated secondary minerals to the other, *i. e.*, from muscovite to chlorite, the specific names depending on the varying amounts of the bases present and ready to enter into combination at the moment of crystallization. As water and magnesia increase, the mineral *thalite* (No. 91B) seems to represent the extreme of the series over against muscovite.

Glauconite. The greensand of the Taconic iron ore was fully described and discussed by Mr. J. E. Spurr, in Bulletin x of the Minnesota Survey. He showed the various microscopic changes that transpired in that substance which resulted in the production of the ores of the Mesabi Iron range. The acumen with which he ferreted out this as the primordial element in the taconyte and showed that both the silica and the oxide of iron resulted from the transition from unstable chemical composition to silica and hematite, the most stable condition of those elements, is worthy of all admiration, and his process and his result will not here be called in question. He presumed, as an ulterior source of the greensand, that it may have been of organic origin, and perhaps depended on Foraminifera, and the writer has given in this volume (page 366) further facts that tend, with a little idealization, to indicate the foraminiferal origin of this greensand. But the greensand was not probably glauconite of foraminiferal origin. According to descriptions and illustrations contained in Part II (Nos. 1276, 1294, 1530, 1630A, 2052, 2138), it is rendered highly probable that this greensand was a more or less devitrified volcanic glass sand. The full discussion of the origin of the taconyte of the Mesabi Iron range is given under that head in the subchapter devoted to petrology.

Sphene. This mineral, when in the metamorphic rocks, is plainly the result of secondary forces, and has resulted from the presence of titanium in older, or original minerals, usually ilmenite or titaniferous magnetite. Such titaniferous minerals result from the disintegration of the original basic rocks, *i. e.*, the greenstones, and have permeated, in greater or less quantity, all the later rocks. That this mineral is, in this sense, secondary also in the igneous rocks in which it occurs, is indicated by its absence in the original rocks, and by its morphologic relations to the minerals with which it is associated. To a large degree sphene has a powerful crystallizing autonomy by reason of which it not only quickly acquires its idiomorphic outlines and remains small, thrusting aside all other elements, but it seldom embraces any other minerals in a poikilitic manner. Yet it is observable, in numerous instances, that it gives way to the outlines of other minerals. In one instance (No. 19H), it was noticed in a dioryte that it was secondary to hornblende, which not only deeply indented its margin, but was enclosed in it in the form of several isolated grains. In No. 1515 it surrounds apatite and apparently some feldspar.

Sphene occurs in nearly all the crystalline rocks except the oldest greenstones, whether igneous or metamorphic, and especially in those with considerable amounts of the dark silicates. It is also found in the clastic rocks, apparently as detrital grains.

Leucoxene represents that form of the alteration product of ilmenite or titaniferous magnetite which is most common in the original basic rocks and in the green schists when they have partially decayed (Nos. 567, 1021, 1022). It is apparently amorphous and remains in this state till metamorphic action recrystallizes it, when it assumes the crystalline characters that are more definitely and usually designated sphene.

Rutile is characteristically a mineral of the crystalline and subcrystalline schists, appearing sometimes in clay slate (No. 395). It favors those rocks in which also exists quartz. It likewise is apparently wholly a secondary mineral, resulting from the recrystallization of the alteration products of ilmenite or of sphene after the abstraction of the lime. The so-called sagenite net of rutile was observed in Nos. 422, 567, 896, 1750, 1814. Twinned rutile was noted in a chlorite schist at Tower, in No. 869, and in an altered or contacting diabase at Wauswaugoning bay (No. 265).

Garnet is one of the metamorphic minerals of the Pewabic quartzyte at Chub (Akeley) lake (No. 1895) and of the mica schists at Little Falls and Pike rapids (Nos. 1670-1673) and occasionally of granite (No. 2189).

Staurolite likewise is found abundantly in the metamorphic rocks at Pike rapids and elsewhere in Morrison county (No. 849 and Mus. Reg. No. 2689). In an altered state it was identified at the contact zone of Animikie slate with a diabase intrusive (No. ——).

Zircon is a mineral of the intensely modified clastics under the action of basic intrusion where gases and solutions were quick to penetrate (Nos. 552, 1902); it also is found in later detrital rocks and gravel.

Fluorite is a constituent of granite at Saganaga lake (No. 2046), and was found in connection with the Keweenawan basic rocks in their contact relations with Animikie, and in veins in the Keweenawan (No. 64A) and in the Archean granite (No. 318).

Olivine. Normally olivine seems to have existed in all the original basic igneous rocks, but it was scattered in small grains or crystals without existing in large quantities. It is also in the secondary basic igneous rocks of the Keweenawan, but in some large areas it is quite sparse in the gabbro, as in the anorthosytes. It is sometimes found in great abundance in the muscovadyte, where it is surrounded with unusual mineral associates.

In the original basic rocks of the Keewatin, supposed to be the representative of the first crust of the earth, and hence the oldest rocks in the state, olivine cannot now be recognized as such, but has been destroyed by the vicissitudes of the long history which it has experienced, some of its serpentinous alteration products only being left to bear testimony to its earlier existence (Nos. 349, 2158).

In the Keweenawan, olivine is not always one of the earliest of the minerals. This occurs in some of the coarse gabbros, or coarse diabases (Nos. 258, 512, 603, 787, 819, 1275, 1828, 1829, 429E) quite frequently, and occasionally it has been noted in narrow dikes (No. 757). This late generation of olivine, compared with that of the feldspathic individuals of the basic Keweenawan, therefore, is not due, apparently, to any batholitic conditions of consolidation, but to chemical conditions inherent in the magma.

Fayalite. That form of olivine which is characterized optically by its negative bisectrix and a distinct cleavage (010) has been recognized in several instances in the muscovadytes (Nos. 1041, 1336, 1343, 1365, 1829, 2058, 2199). This seems to be most common where the rock contains also considerable magnetite.

Bowlingite. Olivine has been seen transformed not only into an indefinite more or less fibrous substance which usually is denominated serpentine, and sometimes into a more definitely characterized mineral (antigorite), but also to the mineral named by Hannay* bowlingite (Nos. 193, 560, 703). Sometimes a grain of olivine is wholly transformed to bowlingite, which takes the form and place of the original, and sometimes a rim of bowlingite surrounds feldspar grains which are also embraced in magnetite, separating the feldspar entirely from contact with the magnetite. This occurs in the cumberlandyte of Mayhew lake (No. 703).

The iron ores—Ilmenite, magnetite. These are mentioned in conjunction for the reason that they seem to be equally old and intimately associated, and have not usually been separately determined in the course of the microscopical examinations. Whether the titaniferous element seen in the secondary minerals, rutile, leucoxene, etc., is dependent on ilmenite or a titaniferous magnetite, or whether the iron ore that occurs sometimes in large masses in the gabbro and in the muscovadyte is ilmenite or titaniferous magnetite, in the majority of cases cannot be stated. On the other

Mineralogical Magazine, vol. i, p. 154, 1877.

hand, it is quite certain that in some instances the ore is almost or quite free from titanium, and usually carries less than the standard amount for ilmenite, and in many of the Keweenawan diabases there is no evidence whatever of the presence of ilmenite, while the cubic crystalline form plainly points to magnetite.

In the original greenstones of igneous origin, these minerals are frequently seen, not only as minerals, but in the form of diffused leucoxene. In the secondary greenstones, when unmetamorphosed, *i. e.*, the clastics either of the Kawishiwin or of the Upper Keewatin, they are very rare, but magnetite in scattered minute crystals has been noted in intimate association with hematite in the jaspilyte ores. When, however, these ores and the rocks containing them are converted to crystalline schists, the Coutchiching, so-called, or the gneisses and mica schists in general, magnetite is the sole form of iron ore that has been observed.

In the Keweenawan gabbro are large masses of magnetite which usually, so far as observed, but not always, carry titanium. Similar iron ore is disseminated through the adjacent gabbro rock in crystals and small masses that vary largely in size and structure. In but few cases in the gabbro, and none in the muscovadyte, has this magnetite been seen to present unequivocal evidence of being of primary or original date, as if crystallizing from a cooling magma amongst the first phenocrysts. On the other hand, it has exhibited in many cases clear proof of its secondary, or at least of its late, origin (Nos. 1, 1C, 5, 6). The original forms of magnetite constitute but a small moiety, and are of microscopic dimensions as crystals. The secondary masses are large, constituting ore bodies that are of promise in economic value. The original crystals are widely distributed in general through the body of the gabbro, or are absent; the secondary masses are usually associated with other evidences of contact relations, and are especially frequent, so far as observed, in association with muscovadyte. The large masses are, in general, believed to be the result of transformation of older jaspilyte lodes existing in the greenstone from which the gabbro itself was derived, while the original minute crystals, having independent cubic outlines, were probably from magnetite (or ilmenite) originally distributed as an essential ingredient in the mass of the same greenstone. In neither case has the iron ore been transferred in any noteworthy amount from the position it occupied in the original greenstone.* It has been subjected to entire recrystallization and has acquired, perhaps, some chemical characters which it did not possess before.

The following figure, drawn from rock No. 1C, shows some relation between the supposed original crystals of magnetite and the secondary accretions. The crystal-

*In *Bulletin vi*, where these ores were discussed, a distinction was made between titaniferous and non-titaniferous magnetites from the gabbro, and it was assumed that the former was indigenous in the gabbro, and the latter masses had been derived from the Animikie as foreign inclusions. Such distinction seems, however, not well supported by field evidence, and cannot be maintained from any other evidence. There is reason to believe that both belong to the gabbro.

line forms of magnetite (a) are surrounded by feldspar (bytownite) and must have had an early date in the formation of the rock. The secondary magnetite is arranged in sheets apparently coincident with the lamellation of the diallage, and penetrated the diallage in proportion as decay of the diallage went on. This alteration probably dated from the cooling period of the rock. It would be interesting to know what relation subsists between the titanium content and the primary or secondary nature of the magnetite, but no investigation has been directed to that point. From the fact that only a *trace* of titanium is reported by Prof. Dodge in the analysis of No. 1, where most of the magnetite is of secondary origin, and that Mr. J. H. Kloos reported that he found "no trace of titanium" in the gabbros at Duluth, it appears that titanium must be of the magnetite dating from the earliest generation. The general absence of leucoxene in No. 1 also accords with this.

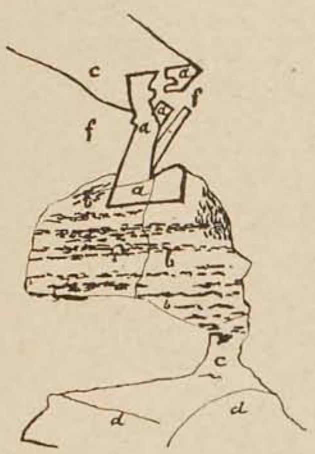

FIG. 55. PRIMARY AND SECONDARY MAGNETITE IN ROCK NO. 1C.

a. Dense magnetite, original(?)
b. Secondary magnetite, in the laminations of altered pyroxene.
c. Changed pyroxene (diallage).
d. Unchanged pyroxene (diallage).
f. Feldspar grains.

Magnetite, therefore, so far as it constitutes rock masses in the Archean, or in the gabbro, is the result of secondary causes, and was concentrated probably from other minerals (largely hematite) by some unusual forces acting at epochs of great metamorphism, applied locally to some preëxisting rock. Such forces have long ago ceased to operate at those localities, and therefore magnetite is no longer in process of formation, but rather of destruction.

Hematite. The oldest recognizable oxide of iron, aside from the magnetite (or ilmenite) of the igneous greenstones of the Archean, is hematite. It constitutes masses of great economic value in the Keewatin, as seen at Soudan, Ely and elsewhere. It is the ore of the jaspilyte, with only microscopic exceptions, where jaspilyte becomes so rich in iron as to be called ore. In the Keewatin it has been presumed by some to be secondary after siderite, and this hypothesis has been applied extensively to explain the origin of the hematite ores of the Taconic. Microscopical examination has shown clearly, however, that it existed prior to the associated siderite, earlier than the magnetite and earlier than pyrite, all of which are found to have had a very early origin in those ores. This is discussed in connection with siderite, foregoing, and it is only necessary at this place to call attention to the prior existence of hematite in the jaspilyte of the Keewatin. This is seen in Nos. 903 and 907, and better still in Nos. 1565 and 1961.

Pyrite. The sulphide of iron at no place in Minnesota, so far as known, is so abundant as to constitute rock masses. It is, however, very widely distributed, extending from the quartz-porphyries of the Lower Keewatin (No. 2238) to those of the Upper Keewatin (No. 387), and from the Archean granite (No. 2248) to the red rocks of the Keweenawan (No. 292), while in nearly all the Archean clastic rocks it is frequent in form of cubic crystals (Nos. 340, 356, 473, 726.) It is so common that it has not been considered necessary to mention it in many of the microscopical descriptions. In connection with the jaspilyte ridges at Tower pyrite seems to exist in considerable quantity, especially in the "south ridge," since its oxidation is palpably the cause of water carrying sulphuric acid, which issues from a drift on the southern side of the ridge. It was also encountered in the (Lee) mine, as evinced by Nos. 1547, 1549 and 2280. In many respects the environments as well as the crystalline perfection of pyrite where seen in the Archean resemble those of magnetite, and there is evidence that it originated in the Archean, where associated with magnetite, at about the same date and by reason of similar or identical physical conditions.

In concluding this sketch of the rock-forming minerals of the crystalline rocks, it may be well to enumerate some general principles brought out forcibly by the examinations detailed in Part II, but which are sometimes not recognized fully by petrographers.

1. *The globular state of incipient minerals.* That quartz assumes a globular form at the commencement of its separation from a magma, and passes through various structures by the extension or the multiplication of these units, was fully announced with illustrations by M. M. Fouqué and Michel Lévy.* These incipient and imperfect forms of quartz appear to arise under metamorphism and continue their development under conditions which obstruct normal growth and especially in the presence of other elements which simultaneously are stimulated to incipient crystallization.

In the course of this investigation several other minerals have been noticed to undergo the same or similar succession of stages. Especially has it been noticed that the globular form is acquired as the first step in the formation of minerals due to metamorphism. We have not had so favorable opportunity to study minerals formed directly from magmas, although many dust-like globular forms have been noted in the zirkelyte resulting from the Keweenawan eruptives. In the devitrification of Keweenawan obsidians, the first forms developed seem to acquire at once angular outlines or thread-like projections.

In the rocks formed from metamorphism which did not reach fusion, it is so common to observe the globular form in the first stage of all the minerals that it seems to be a general law. Owing to the nature of the case this phenomenon is

* *Minéralogie Micrographique*, 1879, p. 193, plate xii, figure 1. The description and illustration given by the authors hardly apply to the globular quartz here referred to, but to a more advanced state of growth. M. Fouqué, however, in his lectures at the Collége de France, has amply discussed the globular form of quartz here referred to.

most common in the muscovadyte, or noryte stage of the gabbro. In this rock, in proportion as one or the other mineral is able to develop more rapidly, it grows beyond the globular state and poikilitically surrounds the globular incipient grains of all the others. This is true of biotite (Nos. 1092, 1777, 638G, 740G), of quartz (Nos. 1039, 1339, 1340, 8M), of magnetite (Nos. 677, 1340, 1343, 2201), of olivine (Nos. 916, 1367, 1343, 505H), of labradorite (Nos. 677, 767, 1345, 1366, 2203, 638G), of cordierite (No. 1092), of augite (or diopside) (Nos. 677, 767, 1092, 1336, 1341, 1089, 2197), of diallage (Nos. 1340, 847G, 857G), of hypersthene (Nos. 960, 1343, 1364, 2203), and of amphibole (Nos. 767, 1345, 2197, 2209, 638G). These included globular grains cannot be considered in all cases as the infantile starting points of the minerals they represent, but in many cases they are grown beyond the infantile dimensions, though they have retained their infantile roundness. It can be seen also that in some instances the formation of a large crystal which poikilitically embraces several others, is made to embrace many minute globular forms of its own kind (Nos. 1092, 1343, 2198, 2209). These latter are very evident when they do not stand in the same orientation as the enclosing crystal (Nos. 2198, 2209), but when they have placed themselves in the same orientation they appear to be lost in the general growth. In case of porphyritic crystals developing from a magma, such increments to the growing crystal would be free to arrange themselves in accord with the polarity of the main crystal. In a plastic or semi-plastic mass, or in a solid undergoing a forced, slow transformation, the various points at which crystallization might simultaneously spring up would be so obstructed by their surroundings that they could not all assume crystalline agreement with each other.

This feature has been observed also in the rhombs of siderite that appear in the jaspilyte of the Lower Keewatin (Nos. 388, 903, 907, 1565) and in that which accompanies the taconyte of the Taconic (No. 1307).

It appears justifiable, therefore, to regard this early globular state of the constituent minerals of a rock as an evidence of metamorphic origin of the rock. Even if this character be seen in but one of the minerals of a given rock, it is evidence of transformation, and all the minerals of such a rock could be looked upon as probably having been developed from an earlier state of the rock.

Owing to the irregular manner of growth which minerals under metamorphic forces are compelled to follow, such grains might be mistaken for "crushed" crystals, and the roundish small parts which have not been able to unite with the larger crystals in uniform orientation might be, and have been in some cases, taken for the debris formed by such crushing. They have also been ascribed to a supposed peripheral action of a flowing igneous rock, the cause being presumed to be the motion of the mass in separating, if not actually breaking, the initial crystals of the different minerals.

2. *"Primary" and "secondary" minerals.* These conventional distinctions have been found insufficient and inapplicable in numerous instances; though they have been employed in the foregoing descriptions, it is only with some misgivings and with a certain amount of recognized vagueness. In general, whenever these terms have been employed, the "secondary" minerals designated are plainly those which have resulted from alteration of other minerals which have been assumed to have been "primary," or "original."

Three different considerations have conspired to render it insufficient, and sometimes incorrect, to apply these terms to the minerals of a crystalline rock.

1. There are three critical epochs in the history of an igneous rock, viz.: the passage from the molten condition to the crystalline, *i. e.*, the solidification, the epoch of cooling subsequent to solidification when it is permeated by gases and suffers rapid metasomatic alteration, and the epoch of atmospheric weathering. Circumstances may be such in the environments of the rock mass that either one of these may be very long, and the changes produced very slow or very rapid. The last mentioned, however, is quite insignificant in Minnesota. Any sample of rock ordinarily procured in the field for examination will be found to pass below the weather effects unless those effects have been abnormally intensified. The glacial abrasion removed the weathering effects and left the surface fresh, and since the glacial epoch, in the northern part of the state at least, the alteration of the exposed minerals has been almost *nil*. It is only in exceptional conditions, such as the local weathering of pyrite or other sulphide, or the oxidation of some carbonate, such as siderite, that the minerals of the crystalline rocks can be seen to be affected by post-glacial decay. Pre-glacial decay is sometimes preserved, and, as will appear, even Archean decay, enters into the history of many rock masses.

Therefore, in so far as the alterations seen in the igneous rocks of Minnesota are able to be classified, they must fall within the two epochs first mentioned above, and they must be referred to the agencies that were then in action. The first epoch (the passage from the molten condition to the crystalline) is not an epoch of alteration which can be said to produce secondary minerals in any sense. There is, therefore, nothing left but the cooling epoch which can be invoked for the explanation of the occurrence of most of the secondary minerals in such rocks in the Keweenawan, viz., quartz, hornblende, orthoclase, chlorite, hematite, most of the zeolites, probably most of the apatite, bowlingite, most of the magnetite and all of the pyrite. In the Archean igneous rocks no secondary minerals coördinate with the foregoing in method or relative date of genesis are known. Considered only from the point of view of Keweenawan history, it can be seen at once that, in ordinary usage, petrographers would differ widely as to the secondary or original nature of many of the foregoing mentioned minerals. The basic magma might acquire acid elements, both before and during the stage of cooling, and the resulting minerals might date all along from the moment of initial solidification to the moment of complete cooling. Quartz, in particular, would be very facile under these forces, and it would be utterly impossible to say at what stage in the history of the consolidation and generation of the rock it took its place in the mass. Again, if the basic magma surrounded and incorporated fragments of acid rock, to what extent would the resulting minerals justly be called original, and to what extent secondary? Some of the included acid material would so penetrate some of the pre-existing minerals as to change them to others. Some basic plagioclases appear thus to have been converted into red feldspars which pass for oligoclase and orthoclase. Augite, under such circumstances, is converted to hornblende and to chlorite. Therefore, as to date and method of genesis there is no criterion to guide in the determination whether such minerals should be called primary or secondary. They are essential parts of a recognized rock mass and they are chemically more stable and enduring than some of the other minerals of the same mass which are recognized as original. The rock in which they exist sometimes is of large amount, and it may have been given specific name, a circumstance which requires that they be regarded as original, whatever their origin or date.

Whatever the uncertainty and confusion that may have attended the generation of these minerals, when considered from the view points of *original* and *secondary*, there seems to be one common element in which they share, and which might furnish them a classificatory designation, viz.: they are the product of mineralizing agents during the cooling stage of the rock.

In order to make plain the ideas of the writer, and not to disturb the prevalent practice of petrographers in the use of the term secondary, the following sketch of the successive dates of the minerals of the igneous rocks of the Keweenawan may be presented:

1. The primary minerals in these rocks are those of the first consolidation, usually porphyritic.

2. Those of the second consolidation, composing the mass of the rock not altered by gases incident to the cooling epoch.

3. Minerals produced after consolidation, during the process of cooling.*

4. The latest minerals formed, *i. e.*, those resulting from atmospheric agents after cooling, *i. e.*, the minerals resulting from atmospheric decay.

*Teall speaks briefly of the fact that the cooling period of an igneous rock must necessarily be one of long duration, but he does not make it, so far as noticed, the birth-date of any of its minerals.

M. M. Fouqué and Michel Lévy, though they make provision for two secondary stages of mineral generation (Minéralogie micrographic, 1879, pp. 151, 152), confine their exposition to primary and secondary stages of *consolidation*, without even giving a definition of the secondary processes, which are simply listed:

"3. Actions secondaires immédiates.

"4. Actions secondaires médiates."

5. Another class of minerals, which may have any date subsequent to those of No. 3 above, are due to dynamic metamorphism in presence of moisture.

The feldspars, labradorite and bytownite, would be *primary*, when porphyritic, also olivine, some apatite and some magnetite.

The most of the rock, including most of the feldspars, usually the augite, occasionally olivine and perhaps biotite, and basaltic hornblende, would come *second* in order, and in this scale would be secondary minerals.

Tertiary minerals would embrace most of the magnetite, the orthoclase, quartz, apatite (in large part), chlorite, bowlingite, epidote and any amphibole.

Quaternary minerals would be such as calcite, limonite, chlorite, sericite, quartz and perhaps some of the zeolites, and numerous others.

Minerals of the *fifth class* are allied in cause and in kind to those of class No. 3, and also embrace some of classes 1 and 2, since metamorphism may be partial or complete and may take place with or without great pressure. When under great pressure the history begins again *de novo* and the primary minerals are reproduced.

These steps in the history of mineral genesis in the crystalline rocks are natural and essential to be recognized. They include all that has been seen and recorded in the mass of special descriptions foregoing in this volume, and theoretically might be expanded so as to embrace all minerals; yet the descriptions have not usually taken these steps into account.

2. The acid igneous rocks, most of which are in the Archean, constitute a very different category as to origin, and necessarily all their minerals share, each with its own ontogenesis in the characteristics of that different history. It is here that the terms original and secondary are specially inapplicable, for in one sense the minerals are all secondary, and in another they are primary, while in another they would mostly fall into the fifth class above. As will be seen in the discussion of the rock masses as such, the Archean acid igneous rocks are traceable to an earlier clastic condition. In many cases the remains of those clastic grains are preserved, and in many others they are so regenerated that but little or no trace of them can be separately detected. They acquire new forms, larger sizes and different composition, in whole or in part. Whether the term original should be applied to the earliest clastic condition recognizable, or to the partly or wholly regenerated condition, or to the earlier non-clastic condition of the (later) clastic state of the separate grains, is a matter which each petrographer would have to decide arbitrarily for himself, and in deciding which he might differ from his fellows.

3. Many metamorphic rocks pass into truly igneous rocks—the gneisses to granites and diorytes, the muscovadyte to gabbro. If principles be adopted for the application of the terms original and secondary to the minerals, say of a gabbro

where usually no trace of an earlier state of the constituent minerals remains, those principles would hardly serve in the treatment of a muscovadyte in which the same minerals can be traced to prior states, nor to the still earlier condition where metamorphism has been so slight that the new minerals can hardly be found, but where a wholly uncrystalline condition pervades the basic debris.

These three difficulties have sometimes been obviated by the non-use of the terms, or by a special description or qualification. If a term could be agreed upon to designate the permanent minerals of an igneous rock which originated during the cooling state of the rock, its use would promote exact definition and be of service to petrographers.

Rareness of shearing and crushing phenomena. The writer has found little reason to ascribe the present condition of the Archean minerals to shearing and crushing subsequent to their formation. These dynamic features are comparatively rare. The shearing and pressure which acted in Archean time seem to have completed their task, and very largely promoted, if they did not provoke, the recrystallization which characterizes the Archean minerals. Such recrystallization completed, the minerals have subsequently, almost without exception, preserved their crystalline integrity to the present day. In their perfection the minerals of the Lower Keewatin went into the conglomerate of the base of the Upper Keewatin, and, aside from the decay incident to the long-continued exposure which the formation of that conglomerate implies, they have persisted till the present, and are identifiable as having come from the Lower Keewatin. Again, the whole Archean, including Upper and Lower Keewatin, was buried under the Taconic, and where the Taconic has been removed or penetrated by drills, the Archean minerals are as perfect, apparently, as when they were so buried. The gabbro and the diabases of the Keweenawan, as well as the rhyolytes and obsidians, when not locally subjected to abnormal conditions, are apparently as perfect in their crystalline and chemical conditions as they were at the moment they acquired their normal temperature.* Throughout all the body of the crystalline rocks, whether of the Archean or of the Taconic, there is little sign either of shearing, crushing, or of decay. The slumber of unchangeableness seems to have settled upon them, awaiting the advent of some great convulsion to start again their energies by imposing conditions of non-equilibrium.†

While stability and long endurance are the characters most easily legible in the oldest crystalline rocks, it is necessary to admit that the Archean rocks have undergone many changes, but those changes are in great measure but local and temporary effects of special conditions or exceptional forces. Belts of folding and

*In rock No. 176 glass still subsists.

†Such instances as rock No. 1011, which may be assumed to be an old Archean diabase, and which contains no quartz, though much altered, rather show that when quartz does enter a diabase it is due neither to age, nor to surface exposure, nor to normal decay (even with dynamic action), and may hence be attributed to that source which is directly suggested in many cases, viz., endomorphism from contact on acid clastics.

of metamorphism have crossed them. Epochs of intense pressure and of crushing have passed over them. These epochs of revolution have been the birth-dates of new minerals. Metamorphism has been carried to complete fusion and the resultant molten rock has solidified as from the molten interior of the earth. But when these revolutions had subsided and the crust had resumed its normal quiet the new minerals and mineral enlargements took on the profound quiet and permanence which have lasted to the present. The changing temperatures of the atmosphere and of the superficial portion of the rocky crust have no perceptible effect below a few feet, and since the Glacial epoch their effect at the immediate surface is very insignificant under ordinary conditions.

Therefore, as a general rule, the Archean minerals are permanent. The only evidence of shearing and crushing pressure that is widely observable consists in the greater or less epochal metamorphism and in the local complete fusion which they have suffered. It will appear that many rocks that have been regarded crushed and sheared crystalline rocks, are more probably sub-crystalline pressed and sheared clastic debris. Permanence rather than change is the normal condition of the Archean crystalline rocks.

(*b*) The Petrology of the Crystalline Rocks.

The most important petrological conclusions drawn from the examination of Minnesota crystalline rocks, detailed in the chapter devoted to microscopical descriptions, are three in number, viz.:

1. The origin of the Archean granite, etc.

2. The origin of the Taconic gabbro, etc.

3. The nature of the greensand that produced the iron ores of the Mesabi Iron range.

Nos. 1 and 2 have been substantially presented in Part I of this volume, and at this place it will be necessary only to supplement that discussion by some further facts and collateral observations. No. 3 is a result reached later, and has taken final shape only in the course of the review and revision incident to the publication of the volume, though attended by the examination of some fresh material.

1. The origin of the Archean granites, etc.

Under the term granite are here embraced all the igneous rocks of the Archean, including dioryte and excepting such gabbros and diabases as are plainly of later date than the Archean, and all other igneous rocks that are not of too basic a composition to be included under the term granite. Quartz-porphyry is also excepted for special treatment.

In the preliminary discussion of this subject, included in Part I of this volume, devoted to "Structural Geology," it is shown that all the structural phenomena of the Archean can be explained on the assumption that the intrusive rocks are metamorphosed conditions of the clastic rocks near adjacent to the observed intrusions, rendered plastic by the forces of dynamic metamorphism accompanied by moisture. As an illustration of this transformation of the Archean clastics some of the field phenomena of the region of Kekequabic lake were enumerated, and in connection therewith is a statement of some of the petrographic facts that accompany and confirm such transition.* The structural relations have also been described in vol. iv, of this report (chapter descriptive of Lake county), and hence it will be necessary here only to mention other petrological facts and inferences bearing on that subject.

1. *Gradations in crystalline structure from granite to graywacke.* It is evident that, while it might be very infrequent to observe petrographic transitions from crystalline to sub-crystalline and to fragmental, *in situ,* owing to the easily movable nature of the plastic or fluid rocks when under the pressure and shearing that produced the assumed plasticity, yet there ought to be found more readily all the varying stages of recrystallization, when the rocks are studied in detail from different localities. Such is the case. One of the most common instances in incipient recrystallization is seen in the graywackes. If the reader will consult the descriptions of the following rock numbers he will find some of the details of this progressive crystallization, viz.: Nos. 341, 2184, 2244, 2245, 2264, 2269, 383G, 386G, 407G, 8H, 389H.

General statements concerning the behavior of the different minerals concerned have been made in the foregoing notes on the rock-forming minerals. It is obvious that under such conditions of alteration and subsequent recrystallization it is impossible sometimes to affirm unqualifiedly that the clastic rock was a typical graywacke. It might have been somewhat pebbly, like a conglomerate, or too fine to bear the name of graywacke. It might have been porphyrel—or arkose; but the special designation of the clastic rock is not important in this connection. Whatever the correct appellation for the rock, the kind of change, tending toward a granitic structure, is the same in all the clastic rocks when they encounter these physical conditions.

2. *The same kind of alteration of quartzyte* is described in connection with the following rock numbers: Nos. 609, 784, 1724, 1839, 1840, 1852, 1853, 1854, 436H. In this series No. 1852 is specially interesting, because of the favorable exposure and the association of the recrystallized quartzyte (Animikie) with a black mica schist which was produced from the Animikie slates under the same forces. The following is from the writer's field book, July 5, 1893:

"1854. I have been on the lookout for evidence to show what becomes of the black slates when subjected to the influences which make quartz-porphyry and red granite of the quartzyte, and I have only found that they

*An earlier discussion of the same subject by the writer was presented to the American Association for the Advancement of Science, August, 1898, and published in the *American Geologist,* November, 1898, vol. xxii, pp. 299-310.

become dense and hard, with much jointing, but here, near the boiler house [Susie island], is a dike of diabase running east and west through the slates. This dike is only ten or twelve feet wide, and, alone, its effect would not be so pronounced, as numerous such dikes have been seen without such effect, but, when its force was united with the deeper-seated action which developed the red granite adjacent, it strongly affected the black slates. In some places the adjacent slates are not only hardened, but on weathering they turn grayish-red, or pinkish, indicating the generation of a red feldspar. In one angular projection, on which the heat of the dike may be supposed to have acted more effectively, there are seen developed some red orthoclase crystals which are scattered through the dense matrix like those of a porphyry. This sample (No. 1854) shows it. This is a step toward showing that the black slates, although less amenable to the change, can be made to take the crystalline condition by contact with the heated traps, and that they also could be made to assume the condition of porphyry and even red granite."

In the formation of a granite from a quartzyte it appears that coarse feldspars (orthoclase) are first formed, embracing the adjacent quartz grains poikilitically. It is obvious that under such conditions only the most acid feldspar could form. Rejecting the surplus of silica, such silica is, perforce, remodeled, and, being an easily mobile element under pressure and in presence of heat and moisture, it takes the spaces left between the feldspars, and thus always appears latest to "solidify." This is in part illustrated by No. 784. The feldspars, however, were a little later to take crystalline outlines than some of the quartz, which sometimes appears in bipyramidal shape quite perfect before the clastic structure is lost (vol. iv, pp. 516, 517). Compare, also, Nos. 609, 611.

3. *The "porphyrel" of the Upper Keewatin* has been one of the most interesting and most studied of the initial rocks that pass into granite. It is specially described, in connection with this change, under the following: Nos. 1061, 1062, 1769, 2189, 2266, 2268, 551G; and in connection with all the rocks named esterellyte, for it is evident that the features of the transition may be studied at either extreme. The megascopic condition of the feldspars in some of the granitic aspects of this transition is illustrated by figure 8 of plate V, taken from No. 776G.

4. Some of the microscopic phases of this transition from *distinctly conglomeratic rock* are mentioned under the following: Nos. 2189, 2245, 2266; and from a siliceous green schist (tuff) under Nos. 1046, 1051, 1052, 1092, 1104.

5. *The transitions from granite to porphyry* are geographical and local, due to absence of "phenocrysts" rather than to any difference in the contents or crystalline condition of the rocks. Compare Nos. 1061, 1094, 776G–777aG.

6. *Granite formed from arkose* is represented by Nos. 344, 923, 994, 995, 2265, but generally has not been specially noted. Of the rocks along the Kawishiwi river Nos. 994 and 995 specially illustrate the consolidation of granitic debris under aqueo-igneous forces and pressure. It is accompanied by the transformation of all the quartz, the generation of epidote and hornblende, and the general granitization of all the rock. The feldspars, while probably saturated by new feldspathic elements, and considerably clouded, are so identically of the same shapes that they can easily be interpreted as old clastic grains.

7. *Gneiss, which frequently passes into mica schist,* has the composition and microscopic character of igneous granite. It is frequently intersheeted with mica schist over wide areas with great regularity, such that there is no possible way of reasonably explaining it, other than to ascribe it to a sedimentary origin and hence an original clastic structure. The straight lines of this stratification sometimes continue visibly without much deviation for the distance of half a mile or more.

This regrowth of feldspars (and other minerals) has not always been interpreted in this way. When seen in a plainly clastic rock such marginal growths have been simply referred to as "enlargements," and when in a crystalline or igneous one, they have been considered either as secondary growths in the original magma prior to consolidation, as zonal increments after the partial resorption, or as renewals of feldspars after partial fusion by a basaltic contact. The indication that springs from our study, however, points to the essential sameness of these renewals, whether in clastic or crystalline rocks, and to the continuance of this manner of crystallization through all grades of development from the most faintly metamorphic clastic to the most perfectly recrystalline igneous.

At the same time, when such regenerated feldspars have been seen in granites, with the "kaolinic" impurities that cloud them driven to or toward their central areas, they have sometimes been supposed to be instances of grains centrally altered through weathering, or some other agency. But several reasons have been given in the previous portions of this chapter for discarding that idea (page 942). It might be stated further that the weathering of a feldspar crystal would begin at the surface and remove its alkaline bases (No. 25Wbis); it would not recrystallize them as silicates in the centre of the crystal. Again, this weather effect, if it be such, appertains to the rock masses at all depths, and is not attributable, in Minnesota, to weathering since the glacial epoch. It is reasonable to ascribe the decay to weathering in Archean time, followed by a powerful reconstructing force by which the alkaline elements once disengaged by weathering were forced into silicated combinations such as muscovite, hornblende and epidote.

As to the effect of dynamic agents, there is no question that they have had great influence in producing the regeneration—*per se,* they could have had no effect in causing the decay. They could not centralize the muscovite in the orthoclases without a profound molecular rearrangement, resulting, when carried to completion, in a re-formation of the whole rock. Such force could have promoted the formation of the secondary silicates (muscovite, epidote, etc.), but could not have separated the elements of those minerals from their former combinations. They might break the crystals, thus facilitating the access of destructive atmospheric agents. It requires, however, both dynamic force and moisture to carry forward the changes which the history of the Archean crystalline rocks shows they have experienced, when all their microscopic phenomena are collated and adjusted into a systematic scheme of interpretation.

Quartz-porphyry. There are two quartz-porphyries to which it is desired to direct attention, as they differ considerably, and are of widely different dates, and are perhaps worthy of separation in nomenclature. One is the oldest known acid rock and the other is the youngest acid eruptive of the Keweenawan. These rocks differ not only in age, but in physical and mineral characters. The former supplied many pebbles for the basal conglomerate of the Upper Keewatin.

The Archean porphyry (Nos. 2229, 2237) is light-colored, weathering whitish. It is mentioned in vol. xiv of this report, where its field appearances are described (pp. 276, 290-293). It exhibits several features of a clastic, at least a sedimentary, or chemico-sedimentary origin. It is not known to act as an intrusive on the older greenstones which lie alongside of it, but it furnished many fragments to the greenstone next younger than itself. (See plate Z, figures 1 and 2, vol. iv. The succession of rocks in order of age is shown by figure 39, page 292.) Its position is between a conglomerate made up exclusively of debris from the Kawishiwin greenstones, and a conglomerate composed largely of debris from itself.

The place of exact transition from the underlying (or southerly) greenstone conglomerate could not be found, but, throughout an interval of a few feet the porphyry along the contact became fine-grained and green, but spotted with rounded fragments of white and red jaspilitic quartz referable to the older greenstone. The transition belt, however, was seen embraced in a boulder, found in the immediate vicinity, which was so suggestive that a faithful drawing and description were taken on the spot (vol. iv, page 291). From the gradually changing characters, whether the greenstone conglomerate or the porphyry be considered, the contact of these two rocks certainly exhibits features that indicate a sedimentary transition. They approach each other in color and mingle with each other in grain, there being three or four larger alternations of the evident characters of both rocks before the transition is complete.

This porphyry also appears, in the field, to pass to a graywacke (No. 2232) and its microscopic characters coincide with that hypothesis. In one place quite plain fragmental structures were seen in the body of the rock (No. 2237), these structures being plainly a part of the rock itself and dying out in all directions.

As to composition, the rock is peculiar for an igneous quartz-porphyry. Its superficial extent, north and south, which is across its width, is about 2,000 feet. Its extent east and west is much greater, but is not known. On the supposition that this rock came from a deep-seated magma, its great amount was sufficient to allow a slow cooling and a gradual crystallization such as to form the granitic structure, but nowhere was a granitic structure observed in this mass, except where it had obviously been regenerated by a later dynamic epoch (No. 2239). Its feldspars are greatly decayed, same as those of graywackes (noted above) and are permeated by calcite, muscovite, epidote, etc. This decay cannot have taken place since the consolidation of the rock, since it is seen uniformly in the rock at all depths and is the same as that often noted in the feldspars of graywackes, and of granites and gneisses resulting from the recrystallization of acid debris (page 942). It is not at the centres of the feldspar grains, but is disseminated uniformly and is much greater than that of the more changeable older greenstones underlying (No. 2227).

The quartz "phenocrysts" are sometimes an inch in diameter, and are rounded, and are sparsely associated with other fragments, such as greenstone, fine slaty greenstone, and of jaspilyte.

The feldspar "phenocrysts" are not wholly of orthoclase, but many of them are of some plagioclase, a fact which is not in keeping with the idea of a great magmatic mass which would have attained a stable and identical composition such as would give origin, on cooling, to a single feldspar as first consolidation.

The rock does not consist wholly of the usual minerals of a quartz-porphyry, but embraces a little biotite, sphene and hornblende (No. 2229).

There is a very striking resemblance in the amount and kind of alteration of the Lower Keewatin quartz-porphyry (No. 2229) to the debris of the same. This is very noticeable at Vermilion lake, where the pebbles of the Stuntz conglomerate can hardly be distinguished in thin section from the finer debris in which they lie. It is an indication that the elements of the oldest quartz-porphyry had already suffered a period of exposure and alteration analogous to that suffered by the debris of the Stuntz conglomerate. It was often remarked that the general aspect, aside from a difference of schistosity, of the thin sections of the original porphyry was so closely like that of those taken from the matrix of the conglomerate, that they could with difficulty be distinguished. There is, indeed, so far as known, no such thing as a fresh quartz-porphyry in the Archean. There is much fresh granite and dioryte and allied coarsely crystalline rock, but, in the quartz-porphyry referred to, the orthoclase, so far as observed, is much altered and crowded with sericites. These alteration products are uniformly distributed in the orthoclases except where the rock has been metamorphosed; then they are grouped centrally in the manner described for the orthoclase of granite.

In order to adjust the foregoing facts with others that show that this rock originated under the action of some great force which was widespread and probably of long duration, the hypothesis was entertained that this rock was due to oceanic sedimentation accompanied by chemical precipitation in Archean time. Its being preceded by a greenstone conglomerate* and followed by another conglomerate (No. 2230; also, plate Z, vol. iv) places it in the midst of rocks of fragmental origin. Its feldspars and quartzes may have been derived by crystallization from an alkaline and siliceous mud of great thickness, the same mud embracing more or less of the regular detritus from the pre-existing Kawishiwin greenstone and jaspilyte. This alkaline mud, following immediately after the primeval greenstones which are supposed to represent the first crust of the earth, was deposited in a hot ocean. It may be supposed that, up to this epoch, the crust had been too hot to allow the condensation of potassium from the surrounding atmosphere, as no potassium exists in the oldest greenstones, nor in the greenstone conglomerate mentioned; and that, cotemporary with the precipitation of potassium into the ocean, was its increased siliceous content of silica, and, later, the copious precipitation of both, the former in a silicated state.

The partial resorption of the phenocrysts of feldspar, the mingling of orthoclase with plagioclase, the fineness of the surrounding matrix, the greatly decayed state of the feldspars, the bipyramidal forms of the quartz, most of these characters usually accepted to indicate igneous origin of the rock showing them, may thus be explained in conjunction with the existence of other features that are usually interpreted as of clastic origin.†

Notwithstanding these facts and inferences, it is necessary to hold the oceanic origin of this quartz-porphyry as only hypothetical until further field examination can be made.

In numerous instances a porphyry which is somewhat granitic, but containing porphyritic quartzes, has been noted cutting the upper part of the Lower Keewatin, as at Ely (Nos. 2095, 2096), and at Vermilion lake (Nos. 2275, 2276), and occasionally the Upper Keewatin, as at Snowbank and Kekequabic lakes. Such "quartz-porphyries" are susceptible of two explanations as to origin, viz.: (1) A compacting and recrystallization of a clastic rock embracing many fragmentary crystals of feldspar and of quartz (Nos. 1062, 2184, 2187, 2189); (2) A transformation, through folding and fracture, of the old quartz-porphyry of the Lower Keewatin (Nos. 2229, 2237), and the production, in that way, of dikes in the later rocks.

The other quartz-porphyry has an origin less doubtful. It constitutes one of the forms of the "red rocks" of the Keweenawan. This is a class of rocks which the writer, following J. C. Norwood, in 1878 and 1879 in several publications showed was derived, as a group, from metamorphic action of the igneous traps on the clastic

*Of this rock, at this place, no sample was taken, but it is represented by rocks Nos. 532H and 626E.

†Note. Prof. W. O. Crosby has suggested a deep-sea origin for the red petrosiliceous rocks, comparing them with the jaspilytes of the Lake Superior region. *Proceedings of the Boston Society of Natural History*, vol. xx, March, 1879.

rocks of the Animikie. Later, Prof. W. S. Bayley made an exhaustive study of the field relations and of the petrology of the region of Pigeon point, and although his first opinion was adverse to that view,* he finally adopted it in full.† He arrived at the conclusion that the igneous quartz-porphyry of Pigeon point is derived from the fusion of the acid clastics, and gives diagrams in which the porphyry intrudes upon the quartzyte from which it is derived. He also shows that the same quartz-porphyry in the same vicinity takes the form of quartz-keratophyre and red granite. This view has already been presented for the origination of the granites of the Archean (above) where the same transitions are manifest on a grand scale.

Several rocks have been described from Pigeon point which illustrate the manner in which the sedimentary rocks are converted to quartz-porphyry. It is found that quartz is one of the first to be affected by metamorphism. It acquires a bipyramidal shape (No. 264) and that almost cotemporaneously orthoclase crystals form, the latter surrounding several clastic quartz grains in a poikilitic manner (No. 1842). Very soon all the quartz that remains is wholly recrystallized, much of it apparently being removed in alkaline solution. More or less biotite and hornblende appear, also nearly all the usual secondary minerals, which, however, here would be called original under the prevalent usage, and in the classification given on page 969 would fall into the fifth class.

There should be recorded here, perhaps, two or three caveats respecting some of the acid igneous rocks, viz.: 1. It is not sufficiently known what is the source of some of the "red rocks" and "augite syenytes" of the Keweenawan. Some of them may come from deeper sources than the Animikie, even from the Archean, although of the date of the Taconic. If they came from some deeper source they would be necessarily dependent on the Archean clastic rocks (perhaps also on some of the Archean igneous rocks) for their chemical composition. 2. It is not yet known how much of the "red rock" series, such as that of the Misquah hills, may be due to a reaction of the acid rocks on the basic of the Keweenawan. A widespread and apparently rather profound endomorphism has affected some of the larger masses of the basic Keweenawan, giving the impression of a later infusion of acid elements. These questions must be left for future students to investigate, but it appears to the writer that such silicified basic igneous rocks may owe their alteration to the fact of submarine extrusion and to the oceanic precipitation of silica which would accompany such conditions.

2. *The origin of the gabbro and its derivatives.*

It was after a conviction had been reached as to the origin of the Archean granites that careful investigation revealed a similar train of evidence leading to the

**American Journal of Science*, 1889, vol. 37, p. 57.

†*Bulletin cix, U. S. Geol. Survey*, 1893.

same origin for the gabbro of the Keweenawan and all its derivatives, viz., that the basic Keweenawan is derived from the metamorphism and complete refusion of the Archean greenstones and their attendants.

The lines of evidence leading to this result are three:

1. Structural field relations.
2. Petrographic and petrologic.
3. General considerations.

The term gabbro as here employed covers all the varieties into which gabbro has been divided, viz.: orthoclase gabbro, quartz gabbro, hornblende gabbro, hypersthene gabbro, olivine gabbro, gabbro diabase, gabbro dioryte; also noryte and its variations, including muscovadyte and its varieties; also peridotyte and pyroxenyte, troctolyte, diabase and diabase porphyryte, and all the basic igneous rocks that have been discovered in the northeastern part of the state, excepting only the Archean greenstones. A rock consisting only of plagioclase and diallage, which are the minerals required to form a normal gabbro, has but rarely been found. From necessity, in the descriptions of Part II the term gabbro has been employed in a broad sense, and sometimes without precise definition. There is no character nor group of characters which can be relied on for persistence to precisely define this term, for the characters mingle confusedly as to structure as well as to mineral composition, if not in the same slide at least in the same visible rock mass, and if not in the same visible rock mass, in the same general terrane or mountain mass. Over a certain area, or little hill, a group of petrographic characters may prevail. In the adjoining hill or on the slopes of the same hill, some of those characters are replaced by other characters, and on the third hill a slightly different change is noticed. On the basis of such variations a diversified nomenclature has arisen. Yet the great rock mass, extending for over a hundred miles in Minnesota, bearing the same taxonomic relations to adjoining rocks, must be considered as one geological entity, having one origin and one history.

There are some isolated areas of gabbro wholly detached from this mass, occurring in the midst of Archean rocks which may not be of the same date as the gabbro mass here referred to. Such are found at Little Falls, in Morrison county, at Knife lake on the international boundary and near Philbrook, in Morrison county. The diabases that compose the bulk of the effusive Keweenawan are considered as extreme derivatives of this gabbro mass; still, one of those diabases and some of the largest of the sills in the Animikie exhibit several gabbroid characters, and at Duluth the Beaver Bay diabase has uniformly been called gabbro.

There are at least three ways in which a normal basic igneous rock may have been modified by the conditions of extrusion, and some of the intermediate rocks above mentioned may have one and some another of these methods of derivation, independently of an intermediate acid state of the greenstones from which they were derived.

1. Complete fusion of contacting acid rocks and the perfect mutual transfusion and molten mixture of the two kinds into a homogeneous magma.

2. The penetration of the acid element into the basic along contacting zones through the agency of mineralizers, during the period of cooling.

3. Submarine extrusion, attended by oceanic precipitation of silica.

Some of the massive quartz-gabbro and augite syenytes appear to have had the first mentioned method of origin.

To the second method may be assigned those that show the micro-pegmatitic structure, and the uralitic state of augite, with chlorite and a reddened state of much of the feldspar.

The third class would include much of the "red rocks." When such basic extrusions were in great amount and were able to crystallize before modification, the resultant rock may have been such as seen in the Misquah hills. When the extrusions were in small amount, and were solidified before crystallizing, the glassy mass was wholly silicified. Thus resulted jaspilyte and probably much of the apobsidians of the Keweenawan.

1. *Structural field relations.* In repeated instances the recognized gabbro mass has been seen to grade into noryte, which (in its normal and usual type) is one of the forms of muscovadyte, the latter term being more flexible and general. This fact is attested by many observers, whether in Minnesota or in Canada, and need not be dwelt on to any length. Yet this noryte has no more stable composition and characters than gabbro, when considered as a rock mass, and in some of its variations it loses its right to the name noryte, and the rock has been given other designations. If the structural relations of noryte to the coarser gabbro be examined it will be found that the transition is both gradual and sudden. The gradual transition is that which has been most frequently observed (Nos. 983, 984), but there are many places along the northern border of the normal gabbro mass where the coarser gabbro rock exhibits a non-conformable contact on noryte masses, *i. e.*, on what have been denominated muscovadyte masses. There is a figure in volume iv (page 303) which illustrates this fact, although, in that instance, the included masses are not typical noryte, but approach a granulitic gabbro. At the time the sketch was made* no specimens were collected at this point, but later specimens (No. 847G) were obtained from the angular included mass by Dr. Grant, who makes the following remark:†

*By Dr. A. Winchell. See *Fifteenth Annual Report*, p. 172.
†*Twenty-Fourth Annual Report*, p. 127.

"The shores of the island in N. W. ¼ sec. 6, T. 64-5 W. [*i. e.*, in Gabemichigama lake] are of coarse gabbro, except for the southern shore, which is composed of fine-grained, granular Keewatin rock, not stratified as far as seen. In one place the gabbro was seen within ten feet of this rock, and the former still retained its coarse grain. At the southwest corner of the island is the locality figured several years ago. The fragments included in the gabbro show no distinct stratification lines. The gabbro is still of coarse grain, even when in small stringers. The included fragments, represented by No. 847G (which also well represents this rock all along the southern shore of this island), are of various shapes and sizes, and many have rounded outlines."

The granulitic structure of the rock in these angular fragments is a "peripheral phase," so called, of the gabbro. This shows that that phase is not dependent on the peripheral action of the gabbro mass, as has been presumed. Again, rock No. 2001, a diabase dike, though having been shattered by contact (evidently) on the walls of a fissure, has a distinct angularity in its minerals, indicating that such friction was not the cause of the fineness and roundness of the grains in muscovadyte and noryte.

The same is indicated by rock No. 8M, which is a finely granular mica schist, produced by metamorphism of the Animikie. It has never been in a fluid state, but shows a similar granular structure, and outwardly resembles some muscovadyte.

At the south shore of Disappointment lake are many obvious transitions from the coarser gabbro to the finer. In some cases the finer rock might be called noryte, or granular gabbro, containing considerable orthorhombic pyroxene (Nos. 2201, 2202, 2203). These transitions are both gradual and abrupt. The rocks are favorably exposed and can be seen for many rods without much hindrance. On a single knob of rock five feet across, standing a little isolated from the main gabbro mass, can be seen on one side a well-developed coarse gabbro, embracing indistinct pebbly forms in smothered outline. Passing gradually across the front of the knob the grain can be seen to grow gradually finer, till, at the opposite side, the rock is quite different, and could be called granulitic gabbro, and embraces distinct pebbly forms. In the field, however, in this instance, this was called pebbly muscovadyte.

The foregoing is probably sufficient to show that in the field the coarse gabbro and the granulitic gabbro (or noryte, when hypersthene is abundant) pass into each other by insensible gradations.

It would now be in order to show that the muscovadyte becomes, when less alteration has taken place, the clastic greenstones of the Keewatin. This is easily ascertained by examining the greenstone belt about Gabemichigama lake and eastward to Flying Cloud lake. One may follow the greenstone eastward from the former lake by a series of small lakes and portages. It forms a conspicuous hill range which, eastward still further, merges into the Giant's range, and westward it culminates in the Twin peaks, south of Ogishke Muncie lake. The route gradually approaches the northern limit of the gabbro, which here has a more northward trend. Finally, making a more careful examination of this greenstone belt, one finds it presents a decided approach toward muscovadyte (Nos. 1778, 1780, 1781) and really becomes the muscovadyte of the region, the change being very evident on following the greenstone eastward till it comes into contact with the gabbro. A similar transition takes place at the northeastward extremities of the narrow lakes through which the Kawishiwi river flows, sections 15 and 16, T. 63-9 W. (Nos. 982, 983, 984), and also in the greenstone hills northward from Chub lake. Indeed it would be entirely correct and safe to state that it takes place wherever the gabbro in its recognized form comes onto or near the Keewatin greenstone.

Again, in some instances, the greenstone is conglomeratic, the pebbles being of different phases of greenstone, of granite and of slate. In such cases, where the original rock is basic enough, the complete transition is easily traceable through muscovadite to the normal gabbro, the pebbly forms being visible in all the rocks. This is notably the case at the point often referred to south of Disappointment lake, described in more detail in volume iv, page 303. Note, also, the pebbly aspect of the granulitic gabbro shown in plate MM, figs. 5 and 6, vol. iv. "This is a remarkable rock, as it resembles muscovadyte, which we suppose to be the result of a change in sedimentary rocks; it is a remarkable circumstance, also, that so far south within the gabbro area so much of this rock is found. It is heavily jointed, lies nearly horizontal and slides in sheets into the lake, toward the southeast, the sheets being from one-half inch to six inches thick. Small nodules weather out on the surfaces, and some larger, harder patches also appear, resembling some seen in the changed graywackes on Gabemichigama lake. This rock prevails about the shores of Muscovado lake, on the shores of the north half of Bashitanaqueb lake, and just north of the latter it forms some high hills."* This is rock Nos. 1784 and 1785. It is evident that here is a large area of the original greenstone, well within the gabbro, which has not suffered a complete conversion to typical gabbro, and that the original greenstone was conglomeratic and similar to that at Disappointment lake.

2. *Petrographic and petrologic.* The petrographic facts have been for the most part enumerated in an earlier part of this chapter in connection with the description of the minerals that compose these rocks. There is nothing more evident in reading the special descriptions of the rocks referred to in Part II, than the "air of family" that binds the gabbro, the muscovadyte, the noryte, or granulitic gabbro, in one genetic class. The ophitic structure of diabase is found to occur in the same rock in conjunction with the granulitic. Sometimes, in the granulitic gabbro, or muscovadyte, the pyroxene is simple augite and sometimes diallage. Frequently hypersthene is abundant and sometimes it is wanting. Sometimes hypersthene is twinned with a monoclinic pyroxene and sometimes it poikilitically embraces labradorite, quartz and globular hypersthenes. Olivine, and even magnetite (No. 695) and biotite sometimes prevail over all the other minerals, in the last making a mica

*N. H. Winchell. *Twenty-first Annual Report*, p. 160.

schist or biotite gneiss (Fifteenth Annual Report, p. 351, and rock No. 983). In all cases, even when a normal gabbro has resulted, the different minerals have a roundish habit, as if cotemporaneously developed. The ophitic structure prevails in those cases where there was a late consolidation or a second generation of augite, and this occurs especially in those masses that have moved more or less from their birth-places, *i. e.*, in the diabases.

There is no single petrographic character that is unique in its mode or geographic place of occurrence within the whole zone, ranging from partially metamorphosed clastic greenstone to typical gabbro, and even to diabase; but the mineralogic composition varies according to some unknown law, or no law, and the contrasting structures often blend in one rock or are associated with minerals which usually are considered divorced from them. This singular rock, or series of rocks, included under the term muscovadyte,* seems to be explicable only on the hypothesis that a variable clastic, though comparatively basic in composition, was subjected to a variable metamorphosing force, the resultant rock being determined by the depth at which the force was applied, the amount of pressure and moisture, the degree of heat and the proportionate amounts of the chemical elements available from place to place for the production of the minerals which now are found in the rock. If at any place any of the oldest (originally massive) greenstones were involved in this metamorphism and refusion, it is probable that the resultant rock would be some of the more basic phases of the general gabbro mass.

In addition to the foregoing general statements as to the confused petrographic characters of the petrologic zone intervening between the Archean greenstones and the Taconic gabbro, there is need perhaps of some specific, recognizable case to which all geologists can be referred tending both to centralize the argument and to elucidate the diversified phenomena. Only referring, here, to the statements made in volume iv, pages 303, 304, respecting the transition studied at Disappointment lake, more direct attention will be called to rock No. 847G, already referred to.† This came from a definite locality and from a rock which has definite relations to a coarse gabbro. It is from the angular masses represented as embraced non-conformably by gabbro in the figure below (figure 56). This figure was drawn from nature by Dr. A. Winchell in 1886, at Gabemichigama lake. The structural relations are described by Dr. Grant, and have already been quoted (page 982). By both this rock was styled muscovadyte, and by the writer it has been described as muscovadyte (page 905), from two sections that have been examined. In the first section it appeared as an ophitic (diabasic) rock. In the second, along with but imperfect

*Two interesting extremes of the family of metamorphic rocks derived from the clastic greenstones are represented by Nos. 399H and 406H.

†The same structural evidence is presented by rocks Nos. 1287 and 1289, at Mayhew lake, the former being a granulitic gabbro unconformable below coarse gabbro.

ophitic structure it has the evident granular condition of muscovadyte. But, so far as the second section shows (it is a larger one), the contained minerals are almost exclusively labradorite and diallage, making the rock a normal and typical gabbro.

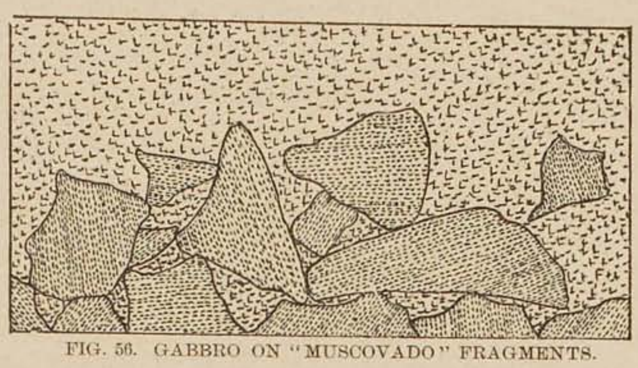

FIG. 56. GABBRO ON "MUSCOVADO" FRAGMENTS.

When it is understood that this rock at this locality is recognized as a part of the metamorphosed Keewatin of the region, and is seen in great amount along the shore of the island, and widely on the mainland, where (as has already been stated) it is traceable directly into the greenstones, it seems to afford unimpeachable testimony, concise and direct, of the change from the greenstones to the gabbro. The facts of nonconformity and intrusive action are only accidents of an epoch of general metamorphism and refusion, and hence do not necessarily separate the intruded rock from the intrusive by any break in genetic relationship.

3. *General considerations.* If these rocks be not thus genetically united, and derived from the Keewatin, there is no possible way known to account for their variations. They include not only the basic rocks that are distinctively greenstone or diabase and gabbro, but more acid phases. Quartz occurs in the gabbro sporadically, likewise orthoclase. In some places hornblende replaces augite, etc., etc. The names that have been given to these and other variations are numerous (see the discussion in Part I), but these various rocks, both geographically and petrographically, shade into each other and into normal gabbro. In order to explain these shades of variation on the hypothesis of differentiation from an intermediate or other primordial magma the different stages of change must have been lost in each other, and, furthermore, they must be allowed to have been cotemporary in the same magma and in opposite directions. This would require such uniformity, and at the same time such variety of primordial magmatic conditions in the same magma that the idea becomes self-contradictory and impossible of rational application. If these variations be supposed to be due to separate intrusion after progressive differentiation had supplied different types of rock for such a result, then those types would not, at the surfaces blend into each other, but one would intrude into the other and show a sharp contrast or contact with it. The general trend of all the facts, both petro-

graphic and structural, when apprehended after long field examination and exhaustive microscopical study, is toward a unity of origin, as to manner and date, of all these variations.

The intermediate rocks. The question may arise—what was the source of the intermediate crystalline rocks? Granite is at one end of the scale and gabbro and diabase at the other. It is true that these extremes have been most studied, both in the field and in the laboratory, and that the foregoing discussion applies essentially only to them. That was necessary. The prime types must first be explained on some rational hypothesis, and the intermediate rocks and all other attendant facts must be assumed to group themselves in some way in rational dependence on them. That seems to be the case. The intermediate rock types, both in the Archean and in the Taconic, blend into the end types. There is no abrupt distinction except locally, and everywhere vanishing distinctions.

If we may judge of the Archean rock terranes before metamorphism by what we see of the Archean now unmetamorphosed, the original rocks consisted primarily of very acid and very basic. There were graywackes (and slates) and greenstones. But there were also basic variations in the graywackes as well as siliceous gradations in the greenstones. Proportionately these geographic belts of transition were of minor importance. The change from a basic clastic rock to an acid one must have taken place somewhat as it does now in the Archean sedimentaries, rather rapidly, and the clastic rocks of intermediate character must have been as rare as they appear to be to-day. Hence, it is reasonable to suppose that, on metamorphism such as presumed above, the resultant igneous rocks would be prevailingly either acid or basic, but that in places there would appear smaller amounts of intermediate igneous rocks.

Consequences of this hypothesis, if true. One of the first and most obvious results springing from this discovery of the origin of Archean igneous rocks, whether acid or basic, is the non-applicability of the theory of differentiation of magmas. Whatever may be the case in other parts of the world, where igneous rocks have been examined from that point of view, there is certainly no standing room for its use in the Archean and Taconic of Minnesota.

Another result of this hypothesis, if true, is to lessen the value of chemical analysis of igneous rocks. Great variations can be found within the muscovadyte belt, running from peridotyte and pyroxenyte to quartzyte and to magnetyte. All these variations can be referred to the varied composition of the original Keewatin.

It also has a bearing on the origin of all the later igneous rocks. The universal greenstone crust would at any epoch in geological history furnish a diabase or a gabbro, should it be affected by such dynamic or other agents as to produce fluidity, and such resultant rock would be uniformly of about the same normal character as the Archean or Taconic diabases. On the other hand all later granites would show great initial variations. If they originate from the Archean they must show alliance with the Archean granites, and with their variations. If paleozoic sediments be fused, or even later rocks, great departures would ensue from the types of Archean granites, and these variations would be emphasized by the greater susceptibility of acid rocks to endomorphism, combined with their greater viscosity. The alkalino-acid element is easily transfused either into (No. 552) or from (Nos. 1B, 5, 648) a molten rock. The ferro-magnesian magma is chemically more stable in contact on acid rocks, but as a molten mass it is more fluid.

The so-called "peripheral phases" of the gabbro are peripheral only by accident. They might occur, and do, at other places in the great mass. The granulitic structure occurs about Muscovado lake, well within the gabbro. The concentration of iron is well known in the coarsely crystalline gabbro, making large deposits. The ferro-magnesian phase in the form of highly magnetited gabbro is the common feature at Mayhew lake and at Frazer lake (No. 1041), while olivine (fayalite) and magnetite sometimes compose important masses (Nos. 1336, 1343). These "phases" have been much noted and studied, but they seem to be phases both of the Keewatin greenstone and of the Taconic gabbro, representing an intermediate state of recrystallization.

The Oldest Known Rocks.

In Part I of this volume it is stated that the oldest rocks of the state are the Keewatin greenstones of the Kawishiwin, and in the preface is a diagrammatic scheme of the structural relations of the Archean as presented in this report.

It is only within a few years that American geologists have entered seriously upon the attempt to subdivide the rocks of the Archean upon a chronological scale. Mr. A. C. Lawson divided the sedimentary Archean of the Rainy Lake region into Coutchiching and Keewatin, the same year in which the writer divided it into Vermilion and Keewatin. In each case it was recognized that there was a later granite which is intruded into these rocks, and Mr. Lawson dwelt on the importance and the significance of this later intrusion. He showed that, either as massive granite or granite-gneiss, this later rock spreads over very extensive areas, and constitutes a large part of the mass which, under the term Lower Laurentian, embraces both metamorphosed sediments and intrusive granite. He restricted the term Laurentian, however, to this igneous rock which, while younger by reason of intrusion, yet structurally in many places lies below the sedimentary rocks of the Archean. The sedimentary division of the Archean was by Lawson designated Ontarian, this term covering both Coutchiching and Keewatin. The earlier division of the "Laurentian," by the Canadian geologists, into Lower and Upper, according to recent researches by Adams, seems to be invalidated, since the Upper Laurentian is found to consist principally of intrusives, such as anorthosyte and other gabbros. However, Logan's separation of the Lower Laurentian into Grenville series and Ottawa gneiss is a distinction which in literature has been maintained. The supposed lower portion, the Ottawa gneiss, is mainly igneous, according to Adams, and the Grenville series is mainly of sedimentary origin.

In the Rainy Lake region Lawson, in the same way, considers the "Laurentian" which invades the Coutchiching and Keewatin, as igneous, and as belonging normally below the Ontarian or sedimentary series. If, however, a careful examination be made into the nature and structure of the Keewatin of Dr. Lawson, it will be found, notwithstanding the apparent parallelism of the succession of the Ottawa region with that of Rainy lake, there is a notable disagreement in structure and succession. As described by Lawson the Keewatin consists of two parts, viz., at the bottom are basic rocks, diabase and hornblende schists. These are followed upward by more acid rocks, but without a distinct line of separation. The whole series is supposed by him to have been primarily of volcanic origin, the nature of the ejecta having changed from basic to acid. This volcanic series he believes is nonconformable upon the Coutchiching which consists of mica schists derived plainly from clastic materials by recrystallization, having a thickness of 22,000 to 28,000 feet. As evidence of this nonconformity he refers to a conglomerate which is nonconformable upon the Coutchiching and lies, as he supposed, at the bottom of the Keewatin. This nonconformity we never could find in Minnesota, but everywhere the Keewatin rocks pass gradually into mica schists. It is therefore a matter of considerable interest that Mr. A. P. Coleman has recently shown that the very conglomerate to which Lawson appealed contains much Keewatin material of older date, and that hence the horizon of the conglomerate is high up in the Keewatin itself.* It is to be noticed therefore, by the removal of this nonconformity above the mica schists, that the lowest known portion of the Keewatin consists, both in the Rainy Lake region and in Minnesota, of what in the Lake Superior region generally has been called *greenstones*.

According to Lawson, and also according to all observations made on this horizon in Minnesota, these greenstones are overlain by a series of volcanic detrital rocks of great thickness, and it is these volcanic detrital rocks, with their variations to true clastic sediments, which, in Minnesota, are extensively converted into gneisses and mica schists by metamorphism. They are parts of the Lower Keewatin. Putting these facts together, it is necessary to come to the conclusion that the mica

**Report of the Bureau of Mines* (Ontario) for 1897. Toronto, 1898, Part II, p. 153.

schists are later than the greenstones rather than earlier, structurally as well as petrographically, *i. e.*, that some portions of the Keewatin are metamorphosed. If the Rainy Lake succession can be adjusted with that of Minnesota, the order will be something as follows:

At the bottom is a greenstone, sometimes massive and igneous, but frequently passing into an agglomeratic condition, with which are associated various other fragmental strata, mainly "greenstone conglomerates," jaspilyte, greenwackes, but also slates and fine graywackes.

The first appearance of acid rock is in the form of a quartz-porphyry (No. 2229) immediately following or in the midst of the fragmental part of this greenstone.

In some places the clastic portion associated with the quartz-poryhyry reaches a great thickness (perhaps 20,000 feet), and by a gradual increase of acid materials through erosion of the quartz-porphyry, as well as by chemical precipitation from the ocean, it acquired a decidedly acid character. A metamorphic revolution accompanied by the production of granite and other crystalline rocks terminated this part of the Keewatin.

There accumulated then a great conglomerate which we have taken as the base of the Upper Keewatin, and which is presumably the equivalent of that described by Lawson and Coleman in the Rainy Lake district. This conglomerate lies sometimes on the earlier granite, and sometimes on the greenstones. Although it would be necessary to infer that it also lies on the strata intervening between the granite and the greenstones, whether they were metamorphosed or not, we have rarely seen it so superimposed, but from the facts stated by Lawson it appears that at Rainy lake it lies on the mica schists (Coutchiching) produced by the metamorphism of those strata. In Minnesota this conglomerate has been called at one locality Stuntz conglomerate, and at another Ogishke conglomerate, before it was sufficiently shown that it is at the same horizon at both places.

This conglomerate is variously mingled with greenstone debris where it lies upon the above mentioned greenstones of the Lower Keewatin, and by the gradual loss of the conglomeratic composition it becomes a clastic greenstone, and as such it acquires great thickness. It appears to have been augmented also by volcanic materials and by further chemical precipitation. In other places the conglomeratic composition is followed by great thicknesses of graywackes and slates. This epoch of the Keewatin was closed by another grand onset of metamorphism and igneous intrusion, which was followed by the Animikie.

Lastly, what the exact manner of transition was to the Animikie is not known, but the Animikie seems to have a basal conglomerate along the southern slopes of the Giant's range; volcanic action was resumed and was widespread at the opening of the Animikie.

While, therefore, in the region northwest of lake Superior we have in the Archean an enormous amount of acid igneous rock, as in Canada, it is found to be of at least two epochs, and in each case to be the cause of, or at least cotemporary with, a profound and extensive metamorphism of the earlier acid clastic rocks. It is not chronologically a part of those clastics, but as a rock mass it is later.

It is to be noticed that there are three epochs of greenstone, viz.: (1) The igneous basal mass which is believed to be the representative of the first crust of the earth. (2) The agglomeratic and fragmental greenstone which preceded and accompanied the first quartz-porphyry. This contains the jaspilyte iron ores at Town. Volcanic action added largely to this greenstone. (3) The greenstone of the Upper Keewatin. This is usually distinctly clastic, and is also in some part of volcanic ejecta.

The writer has elsewhere shown* that, as a mass, these greenstones are predominantly of fragmental structure and of volcanic origin, but also embrace truly massive rocks. The term Kawishiwin, used by the Minnesota Survey, embraces the first two above, being those of the Lower Keewatin.

3. *The nature of the greensand that produced the iron ores of the Mesabi Iron range.* It has already been stated that the original greensand of the Mesabi Iron range, the source of the hematite now extensively wrought in northern Minnesota, was probably not derived from organic agencies. It was the suggestion of Dr. J. E. Wolff, adopted by Mr. Spurr, that this substance is glauconite and hence might have been the product of foraminiferal organisms (Bulletin x) and that suggestion has generally been accepted, at least by the officers of the Minnesota Survey. It was through the careful inductive research of Mr. Spurr that the ultimate source of the ore was found in this greensand.

In the course of the microscopical work embodied in this volume several discoveries have been made which, at first disregarded or otherwise explained, have led to the abandonment of the idea that foraminiferal organisms were responsible for the greensand. When these new facts are adjusted with others that were known before, but which, appearing anomalous, were disregarded or otherwise explained, the greensand appears to have resulted from a volcanic sand, and the taconyte rock itself, both the granular and the massive, from igneous forces.

This conclusion is as much a surprise to the writer as it can be to any one, since he has formerly considered the origination of the hematite of the Mesabi range definitively traced to an organic origin.

Attention may first be directed to some facts, in part mentioned by Mr. Spurr, which unite with others since noted, to compel to the new view.

* *The origin of the Archean Greenstones, Twenty-third Annual Report, Minnesota Survey*, pp. 4-35, 1894.

Anomalous megascopic facts. 1. The iron-bearing rock is, as a whole, non-clastic in its present condition. It is only by inference that it can be said ever to have been clastic. This applies more forcibly to the rock known as non-productive taconyte than to the rich ore lenses, for there is in the ore bodies an overspreading, general, bedded structure which indicates sedimentation, especially in the granular portions. Both above and below the iron-bearing member are plainly clastic rocks, and occasionally some clastic grains are seen near the upper and lower surfaces of the iron-bearing rocks. These facts indicate the general prevalence of detrital agencies. It leaves room only for the inference that the iron-bearing rock itself was of a peculiar composition.

2. The unproductive iron-bearing rocks are divisible into two kinds, viz.: (1) A massive homogeneous, but rudely sheeted or bedded, gray or brownish-gray, fine-grained rock (Nos. 1688, 1692), in which appears very little or none of the characteristic globular or any other fragmental structure; and (2) The rock which is distinctly granular with colored or limpid round globules, one of the characteristic structures of taconyte (No. 852B). There are intermediate structures, apparently, and the globular forms, or others resembling them, occasionally are seen in No. 1. The globular form constitutes, when the iron is fully developed, the bulk of the "soft ores" of the western part of the Mesabi range. No. 1 prevails at the eastern end of the Mesabi range, where it also varies to a jaspilyte.

3. There is a marked basaltic, columnar structure which has been fully described by Mr. Spurr in Bulletin x, pp. 164–167 (Nos. 648, 658). His description in all respects, except as to his assignment of cause, could be applied to numerous basaltic obsidians or lavas. He says: "The typical jointing of the iron-bearing rocks has all of these characteristics," *i. e.*, the characteristics of the basaltic jointing of "igneous rocks of an effusive or intrusive nature." An instance of this columnar structure was noted at Prairie River falls in 1889 by the writer, and three of the specimens collected there by him (No. 1527) are shown, from photograph, on plate IV, figure 1. The columnar structure involves both globular-granular and non-globular forms of the taconyte.* The order of parts from Nos. 1530 to 1525, in descending order, when interpreted in the light of the latest developments, is as follows:

No. 1530. A coarse, evidently fragmental, rusty, siliceous, somewhat vesicular rock. The five samples of this rock collected, and now in the museum of the University, consist of globular taconyte, but with some spreading, irregular masses, suggesting breccia or lapilli in the midst of volcanic sand. One specimen shows a banding that might be due to variation in sediments. See plate III; also, page 739. Originally a volcanic sand.

No. 1529. Peculiar "streamed" and brecciated mixture of chalcedonic quartz, globular taconyte and geodic quartz, the last filling original elongated cavities, which are embraced entirely in a casing of white "chalcedonic" quartz. This seems to be from the superficial part of a lava flow where volcanic (glass) sand accumulated amidst the breccia. Some parts of this rock are like the banded jaspilyte of the Vermilion range; four specimens.

*Other interesting features of this rock at Prairie River falls are mentioned in the annual report for that year (the *Eighteenth*) p. 15.

No. 1528. Very similar to No. 1530. This is about at the horizon of No. 1527, but the specimen shows no basaltic jointage. Largely from volcanic glass sand, but showing original variations in the sand, some of it being still isotropic. Some of the quartz is coarse and may have been originally fragmental, but it is now wholly interlocked with the matrix; one specimen.

No. 1527. The globular structure is visible on most of the freshly fractured surfaces. This is basaltically jointed.

The whole thickness of these beds is, visibly, but about five feet. Between them and the first outcrop of the Pokegama quartzyte is a short interval unexposed, the rock of which is unknown. The quartzyte (Nos. 1525, 1525A and 1526) is supposed to underlie the foregoing, but it may overlie. In this quartzyte are isotropic globules and areas which are ascribable to volcanic glass, also tourmaline which indicates solfataric action. Compare the microscopical descriptions.

4. The description of the Pokegama quartzyte published in the Eighteenth Annual Report (pages 15–18) combined with a re-examination of specimens collected (Nos. 1525–1535) leads to the belief that it is not wholly below the iron ore, but cotemporary with and later than some parts of the ore. It was also later (on the evidence of pebbles which it contains) than some rock (not from the Archean) which appears to be from the Keweenawan. In short, the conglomeratic parts of the Pokegama quartzyte (No. 1532), which parts, so far as known, are near the upper limit of the quartzyte, are perhaps of the age of the Puckwunge conglomerate, and therefore later than an important eruptive part of the Keweenawan. The ore at the Diamond mine, eastward from Prairie River falls, is in a quartz sandstone (No. 1534) and is overlain by a fine red unctuous shale (No. 1533) that is like some seen in the Keweenawan.* This ore has not the distinct taconitic structure seen in the hematite at Prairie River falls (No. 1527) although it fades out in the fragmental sand in the form of roundish grains as if it had a taconitic (globular) origin. While it lies higher than the quartzyte, that which is seen at Prairie River falls and has a basaltic structure may belong below the quartzyte.

5. There is a suggestive slatiness parallel with the general dip, which is like that known to pervade surface igneous rocks. It is comparable with that seen in the igneous felsitic slates of Pennsylvania, discussed by Prof. George H. Williams,† and by Dr. F. Bascom.‡ This is also fully described by Mr. Spurr, in Bulletin x, pages 167–172. The minuteness of his description is so exact that one can easily attribute some of the characters to spherulitic parting planes in a surface lava, and in general the whole cleavage to that of a streamed surface lava on slow cooling.

6. A volcanic epoch on the south side of lake Superior has been described§ on the Penokee iron range (the parallel of the Mesabi) by Prof. C. R. Van Hise (No. 1939),

* See figure 2, *Eighteenth Annual Report.*

† *American Journal of Science*, third series, vols. 44 and 46, 1892 and 1893.

‡ *Bulletin cxxxvi, United States Geol. Survey*, 1896.

§ *Bulletin of the Geological Society of America*, vol. iv, p. 435, 1893 (distributed in 1894); *Monograph* xix, *U. S. Geol. Survey*, 1892, pp. 360, 379.

who states that the volcanic fragmentals are interbedded with the iron-bearing rocks. Of this region there has been a careful study of the structural relations. Clastic and non-clastic sediments are mingled with distinctly igneous materials which are sometimes in the form of lava flows and sometimes as "greenstone conglomerates," and sometimes non-conglomeratic. This volcanic material is sometimes embraced in a matrix of non-fragmental quartz, which is taken as evidence that the rock was formed under water.

7. The supposed glauconitic greensand is anomalous in containing little or no potash (Bulletin x, Minnesota Survey, page 242) and in approaching in composition that of a highly ferruginous basic obsidian.

8. Very much of the iron-bearing rock, especially the low-grade ores, is not taconitic (Nos. 1688, 1692), but irregularly stratified and amorphous (No. 1 under No. 2 above). Yet it exhibits the same kind of transitions from rock to ore as those parts which are distinctly globular in the characteristic taconitic manner. Mr. Spurr has collected some of these non-taconitic rocks, viz.: Nos. 128S, 148S, 149S, 204S, 210S. They are represented by various numbers in the series of all the geologists. Indeed, by far the greater amount of the iron-bearing rocks of the Animikie consists of this gray, non-taconitic, siliceous, non-productive rock. Besides this prevalent rock, the jaspilyte which is banded like that of the Vermilion range is non-taconitic. This is distributed from one end of the Mesabi range to the other, but occurs nowhere in so large amounts as in the Vermilion range. The question arises as to the origin of this rock, for the glauconitic source can apply as a whole only to the taconitic part of the series.

Anomalous microscopic facts. 1. One of the most interesting microscopic facts is the obvious and abundant origination of minerals, such as actinolite and epidote, containing important amounts of magnesia and of lime, from a supposed glauconite containing very small percentages of these bases, coupled with the non-occurrence of any alkali-bearing minerals, although a normal glauconite contains from two to seven per cent of potash (Bulletin x, page 227).

2. On the theory that the ore is derived wholly from glauconite, or from any substance undergoing metasomatosis, it is singular that in the resultant rock there should be not only more iron, taken in the aggregate, than there was in the total of the glauconite, but vastly more of quartz as well. This remark can be appreciated fully only by one who is acquainted with the field appearances. If the widest allowance be made for an imagined transference of these substances from one place in the rock to another, the concentration of quartz in one place and of iron oxide in another, the transfer still falls far short of accounting for the supposed result. The formation is now, practically, totally pure iron oxide or pure quartz. Had it

consisted originally of a substance containing, say 50 per cent of silica and 25 per cent of iron oxide, it has lost 25 per cent of its substance, and, without additional supplies, it should show evidences of reduction of bulk to that amount. No such contraction has been noted. On the contrary, Mr. Spurr discovered evidences of expansile movements, owing to the introduction of foreign substances, chiefly siderite, the whole increase in bulk, due to this cause, being estimated at "about one-tenth of its former volume" (Bulletin x, page 163).

A subsequent decarbonatizing he assumes to have been the cause of shrinkage which produced the prevalent columnar jointing—a phenomenon that we prefer to attribute to shrinkage caused by a loss of heat.

Again, in all cases observed microscopically, by Mr. Spurr or by the writer, when siderite is associated with the oxide of iron (excepting limonite), it has been found that the carbonate was later formed than the oxide. This assumed cause for the present megascopic columnar structure requires, on the contrary, that the carbonate precede the oxide.

Additional facts. When the iron-bearing rocks collected about Gunflint lake were first examined microscopically there were seen sundry things that suggested igneous origin, and others which strongly indicated the agency of volcanic forces in the vicinity. These were not fully understood at first, and were passed by as minor anomalies which might be due to other causes. But as these signs multiplied and were finally found to converge in an igneous rock, it was plain that it was necessary to reopen the whole question of the origin of the iron-bearing rocks of the Mesabi Iron range. It then became necessary to revise, before publication, the descriptions of numerous rock sections, incorporating and interpreting the anomalous facts and uniting them with other features observed later, and to point out more fully their significance. Such revision and its results are included in the foregoing descriptions (Part II), and they will be summarized briefly as follows:

1. The rock No. 307 first attracted attention. It is described (page 309) as a tuff, with a query, and is compared to a Carboniferous tuff of King's county, Ireland, of which a small fragment had been obtained of Sir Arch. Geikie. This tuff is found near the northern limit of the Animikie on a point on the south side of Gunflint river, west of "the narrows." It is illustrated by the photograph, figure 9, plate V. This indicated the existence of volcanoes in the region at the time of the opening of the Animikie. This tuff is not silicified, and is believed to have rested on a land surface.

2. In rock No. 312, which is mostly composed of siderite, and which is represented from a photograph in plate VI, are found not only ragged pieces of rock like No. 307, but also many pieces of jasperoid or gray flint, or devitrified glass (Nos.

1310, 1311). This siderite is continuously coated with a rusty film from the oxidation of the carbonate of iron. The flinty inclusions are not thus coated. It shows a sedimentary structure. Hence it was formed under water, either oceanic or of some local lake, probably the latter. Into that water were carried pieces of volcanic glass from the adjacent land surfaces. These flint pieces are not taconitic. It was found afterward that a similar breccia-conglomerate is rather widespread, and sometimes becomes so fine that its constituent inclusions are globular grains no larger than those of taconyte (Nos. 818W, 436H).

3. The carbonate matrix is replaced by one of chalcedonic quartz (No. 436H), and in such form this conglomerate composes thick horizontal beds in the Animikie,* indicating that the siliceous matrix was formed in larger bodies of water, probably in the ocean from which was precipitated chemical silica. In other places the quartz matrix is mingled with the carbonate matrix. In the carbonate matrix is sometimes a thin layer of fine volcanic tuff similar to No. 307 but grayish green instead of black. This difference of color is attributable to its having been deposited in water instead of on a land surface.

4. This fragmental phase of the Animikie varies still further. It is composed sometimes mostly of rounded quartz grains (No. 1322) rather coarse; and in this rock are but few grains or pebbles of devitrified glass (figure 9, plate II). Such rock must have been formed largely from the Archean adjacent, but in part from erosion of silicified igneous rocks (of the Animikie ?). It demonstrates that, earlier than the fragmental parts of the Animikie, which include all globular taconyte, was a mass of glassy igneous rocks, and that that earlier rock was probably the same that supplied flint fragments to the siderite (No. 312) illustrated by plate VI.

5. There are all degrees of proportional gradation between rocks Nos. 1322 and 1319, one containing mostly fragmental quartz from the Archean, and the other mostly fragmental devitrified pebbles from silicified rhyolytes.

6. In No. 1319, as well as in many other taconitic rocks from the vicinity of Gunflint lake, are all degrees of proportional gradation between complete silicification of the component globules and an almost amorphous glassy condition. The same occurs generally in the taconyte of the Mesabi range, but not always in the same rock mass. This shows that the source of supply of these original globules was originally partly silicified and partly not silicified, and hence it is an indication that such may be the case widely on the Mesabi range. These globules are of the same size, originally of the same nature, and since incorporation in the rock have been under the same conditions. If they differ now, they must have differed when they were introduced into this rock, by the same reasoning as shows a difference of origin of the grains of

*H. V. WINCHELL. *Seventeenth Annual Report*, p. 104.

the rocks Nos. 1322 and 1319, mentioned last above. In both cases there has been an intergranular later introduction of interlocking quartz, cementing the rock into a dense taconyte or taconitic quartzyte.

7. In several instances this older rhyolitic rock has been seen in the vicinity of Gunflint lake. It is identical with that already mentioned at Prairie River falls (No. 1529), and is illustrated by No. 435H, and by several of those of No. 720W. This always lies near or directly upon the Archean. It is a jaspilyte, identical in all respects with the normal jaspilyte of the Vermilion Iron range, but varying to felsyte, and finally to less siliceous slate or flint, and to a dark rock which has not been carefully studied. This rock is never taconitic (globular), but streamed and striped like a fine-grained rhyolyte, showing white and red bandings, which are accompanied by thin sheetings of magnetite or hematite. It is this which has furnished the silicified pebbles of the globular taconyte, and it is the original (glassy) condition of this which furnished the non-silicified globules (or glauconite) of the granular taconyte.

The most remarkable exhibition of this rock is to be seen at a point on the shore of Black Fly bay, which is an appendage of Gunflint lake on the Canadian side, where it can be seen lying immediately on the Archean granite, presenting beautifully colored, sharp, fluidal contortions. A bluff which occurs a little further north, illustrated by rock No. 720W, consists largely of this rock in a brecciated condition, somewhat mingled with sedimentary debris of rock like itself, and in those places showing the characteristic globular composition. This bluff is thus described by A. Winchell:*

"S. E. ¼ sec. 18, T. 65-3, as of Minnesota, just south of the cape. A remarkable display. In a rounded, naked bluff, fifteen feet high, is seen the aspect of a conglomerate with many whitish constituents. Examination shows it to be a portion of the slate formation [*i. e.*, of the Animikie] contorted in a striking manner. The laminations are still preserved and serve to evince the disturbance. There are some quartzose layers, and some quartz veins. Much of the slate has assumed a flinty constitution, and some laminæ are of red jasper. There are patches of what I have called oölitic magnetite, and areas in which the spherules are sparsely scattered in a somewhat homogeneous matrix of undetermined character. In some places the crystalline magnetite sparkles brilliantly, and there are others in which it has been oxidized by water and burnings [of the forest] into a crumbling ferruginous mass, like the waste of a hematite mine."

The specimens collected, fourteen in number, show all these features.

8. There is a curious iron-bearing rock (Nos. 1896 and 879G) north from the line of strike of the recognized Animikie, near the late workings of the Gunflint Lake Iron company, lying in or on the Keewatin greenstone. Whether this belongs with the Keewatin or with the Animikie is immaterial to the point to be mentioned, since it is plain that the ores of the two formations had an identical manner of origin. This ore, while presenting some of the taconitic characters of the Mesabi ore, yet embraces igneous minerals, such as pyroxene. As an Animikie rock it may have been a lava which locally came into contact with volcanic glass sand (and perhaps other kinds) which it incorporated into its mass. On silicification the pyroxene was exempted from the usual change. As a Keewatin rock it may have been a detritus of jaspilitic sand and greenstone debris which, on metamorphism,

* *Sixteenth Annual Report*, p. 241.

gave origin to the poikilitic and globular pyroxenes. In either case the rock is a mixture of ferruginous (originally clastic) taconyte with elements that are distinctly igneous or metamorphic, suggesting close relations in the origination of the two kinds.

9. Lastly, the crucial evidence was found at a point about a mile west of Gunflint lake, described and illustrated by figure 54, on page 951 (Nos. 1897, 2052 and 2053).

A sideritic rock (No. 2052) makes quite a display in a conspicuous hill. It is the iron-bearing member or its representative, and shows red because of the oxidized surfaces. It is broken by later diabase intrusions which afford a varied manner of contact on the sideritic slates, the diabase being coarsely porphyritic. This sideritic rock passes with the dip southward and becomes a breccia of confused composition. In the hill (No. 2052) it is somewhat actinolitic. At the railroad cut (figure 54) it is almost wholly of actinolite, but still has so much siderite that it turns yellow with iron rust (Nos. 1897, 2053) and it contains many quartzose flinty masses, some being two feet long. In the matrix of this quartzose breccia the above sideritic rock becomes not only actinolitic but diabasic and glassy (No. 2053). So far as can be judged from the field-notes, and from the thin sections examined, the sideritic iron-bearing member passes through an actinolitic phase and afterward acquires the form of a basic volcanic glass, from which, on cooling, were formed small spherulitic segregated masses like those of the lava sheet of Grand Portage island (No. 544).

It is apparent, therefore, that the iron-bearing member has various phases, especially when it is not economically productive, viz.:

(a) It is a basic glass.

(b) It is a jaspilyte, or silicified basic rhyolitic lava.

(c) It is a sideritic rock (not fragmental).

(d) It is an actinolitic siderite.

(e) It is a sideryte (clastic or chemical precipitate).

(f) It is a breccia and a conglomerate of basic glass and of jaspilyte.

(g) It is a taconyte, or sand of volcanic glass and of jaspilyte.

(h) It is a nondescript gray, greenish-gray, or often brown, rudely bedded siliceous rock (allied to c).

All the foregoing anomalous as well as the additional facts may be explained by the following hypothesis:

A chain of active volcanoes, having explosive emissions, extended across northeastern Minnesota about where the Mesabi Iron range is found. This was near the shore line of the Taconic ocean, and was accompanied by land-locked bays, and perhaps by fresh-water lakes. Such marginal volcanoes had a chemical effect on the oceanic water, causing the precipitation of silica and probably of iron. Its basic lavas and obsidians were attacked by the hot waters and were converted by encroaching silica into jaspilyte. Near the shore such glassy lavas were eroded by wave action and distributed so as to form conglomerates and sandstones. Such action would have distributed lavas wholly silicified as well as those which were yet glassy, and the detritus of both would necessarily mingle with detritus from the Archean. Such lavas would exhibit great contortion, and in places great brecciation, the same as later lavas, and these breccias must have been mingled sometimes with the products of detrital action. After prolonged activity of the volcanoes most of the deposits and of the lavas which were submarine would be permeated by secondary silica, but carbonate of iron would permeate the mass where carbonic acid had freer access, as in the lagoons into which streams drained from the land surface to the north.

Consequences of this hypothesis.

If this hypothesis be true, certain results follow, bearing on the structural and chemical geology, and on the future economic development of the ores.

1. We probably see only the northern border of the iron-bearing rock. The original basic lava, as well as the resultant volcanic sand, would probably accumulate in greater quantity to the south of the volcanic belt than toward the north. We know nothing about the location of the original craters. They may have been to the north of the present line of strike of the Animikie or further south. Wherever they were, it is evident that the accumulation of the larger deposits of volcanic sand would be to the southward of the larger deposits of lava. Where the lava form of the iron-bearing rock subsists still in the Mesabi range, as through much of its eastern extension it is reasonable to look for globular taconyte toward the south further, even if the surface rock be of the slates of the Animikie.

2. This volcanic epoch may have a deep-seated connection with the Cabotian of the Keweenawan.

3. It renders it probable that the igneous layers in the black slate about Gunflint lake are not all intrusive sills, but may be in part cotemporary with the fragmentals.

4. An intimate alliance in mode of origin is shown between the ores and much of the ore-bearing rock, of the Vermilion and Mesabi ranges. This brings to mind the views of M. E. Wadsworth, who first argued for the igneous origin of the jaspilyte of the Marquette region. His evidence consisted of what he considered intrusive relations with the adjacent rock, and he supposed the present nature of the rock is that which it had when molten. The writer has shown elsewhere that both these ideas are incorrect, and that much of the Vermilion jaspilyte is a bedded oceanic precipitate, probably analogous to the bedded flints of the Animikie. However, Dr. Wadsworth is to be credited with the first suggestion as to the manner of origin of the igneous portion of the jaspilyte. This includes that which is much contorted

and banded in the manner of rhyolyte and not that which is interbedded with greenstone debris, or which passes into argillyte or other rock by slow changes.

5. Although these volcanoes may have begun as submarine, the surrounding areas must have been elevated gradually above the ocean level. Their lavas then would have remained largely unsilicified, and they may have flowed great distances.

6. Why are some lavas silicified and others not? Without going into this question any further, it may be well to suggest some causes for this difference: (a) Some flows may have been submarine and some terrestrial. (b) Some may have come from volcanoes, at first submarine, and some from fissures that never formed volcanoes. (c) Some lava layers may have been very thick—too thick for complete oceanic silicification.* In that way large bodies of "red rock" may have been formed. (d) The great dynamic fracture line may have been shifted, as stated in the preface of volume iv (page 17), to the south. Indeed, the Beaver Bay diabase and all later (Manitou) lavas may have been ejected from such later fissures.

7. The ore bodies are likely to be found in the vicinity of the ancient craters, where oceanic precipitation was most copious, and hence in varying amounts on the same stratigraphic horizon.

8. Although to a small extent the process of alteration may have continued to the present, the bulk of the iron, as of the quartz, of the iron-bearing rock, must have originated during the period of volcanic activity.

Note. Circumstances render it impossible to thoroughly digest the new issues involved in the adoption of this hypothesis. That it bears an intimate relation to the Animikie, the disappearance of which throughout a long tract in Minnesota has caused much difficulty of interpretation, and to the whole "red rock" series, especially to the more massive parts of the "red rock," is at once apparent. It brings the flinty layers of the Animikie, along the northern strike of the Animikie, into relation with eruptive causes, and suggests that the Cabotian age of igneous activity may have been (or at least begun) in early Animikie time; and that involves the definition of the Keweenawan.

* The silicification of trees, a common feature of some parts of the western United States, especially in Arizona, seems to be a similar phenomenon.

APPENDIX.

(A)

The Structure of the Keweenawan.

A large mass of notes has accumulated in the course of the field work, as well as in the subsequent study of the rocks of the Keweenawan, bearing on the succession of the parts of that formation. It was once designed to review that subject more thoroughly than has been done in the discussion in Part I. There are sundry references in the body of Part II to such intended review, but the chief points only will be presented, with short references to preceding pages where illustrative facts are mentioned.

1. The tendency of the evidence has been to increase the bulk of the surface lavas that preceded the Beaver Bay diabase, and hence toward the separation of the Beaver Bay diabase from the gabbro mass of the northern part of the Keweenawan belt in Lake and Cook counties, in chronologic birth as it is in geographic place. (Compare Nos. 522, 523 and 525.) It seems, therefore, that there are two main series of alternating traps, sandstones and amygdaloids, one in the Cabotian and one in the Manitou. The knowledge we possess of the geology of the country immediately back from the shore line of lake Superior is too meagre to warrant an attempt to define these two series.

The Beaver Bay diabase may be credited, therefore, with some of the phenomena which, along the lake shore, have been ascribed to the earlier gabbro, such as the production of red rock, as at Grand Portage, and perhaps at Pigeon point; the production of the great dikes at Grand Portage and the great sills of the international boundary in Cook county. This great mass has very widely been called a part of the original gabbro, and it cannot at present be separated from it either geographically or petrographically, although it seems to be separate from it stratigraphically. They both belong in the Cabotian, as defined, but the Beaver Bay diabase may have to be separated from the Cabotian.

2. *The age of the Logan sills.* The age of the sill north of Birch island (Nos. 263, 265) is the same as that of the great east-west dikes. The latter are earlier than the conglomerate at the base of Grand Portage island, as their debris and the "red rock" which they formed are in that conglomerate. Therefore, the sills of the region, and probably all the Logan sills, *are not later than the Keweenawan.*

(B)

Additional Petrographic Descriptions.

No. 1527. Hematite. *(Taconitic.)*

Prairie River falls, S. E. ¼ sec. 34, T. 56-25 W.

Ref. Annual Report, xviii, pages 15, 60; Bulletin vi, pages 120, 422; Final Report, v, pages 737, 991; also plate IV, figure 1.

Meg. Basaltic hematite.

Mic. The globular structure characteristic of taconyte is very evident. It becomes less evident in the crystalline massive hematite, but still it can be seen both in transmitted and in reflected light that the globular structure pervades the whole. The fine, scattered, angular spaces lying between the original grains, even in the massive hematite, are occupied by the usual fine *quartz* mosaic, showing that the same oceanic precipitate penetrated even amongst those grains which were converted entirely to *hematite*. One section.

Age. Animikie (iron-bearing member). N. H. W.

No. 1689. Tuff.

From the Cincinnati property, Mesabi Iron range, sec. 2, T. 58-16 W.

Ref. Annual Report, xxi, pages 118, 155; Final Report, v, page 760.

Meg. Coarsely tuffaceous; generally dark, or greenish-black, some of the original angular fragments being about an inch in longest diameter and of a flinty fineness. From this size these flinty pieces graduate downward in size and become the taconitic globular masses characteristic of the rock bearing the Mesabi soft ores. In some parts these taconitic globules compose the most of the rock, though with a liberal supply of magnetite.

Mic. The section made is so thick that the taconitic globules are for the most part wholly non-transparent. It serves to outline the globules, and to show the inter-granular *quartz* mosaic which is in part replaced, in a narrow border about each globule apparently by fibrous rusty *actinolite*.

Age. Animikie; iron-bearing member. One section.

Remark. This rock reveals the former activity of volcanoes in the region now occupied by the most valuable mines of the Mesabi Iron range. Connected with similar evidences presented for the extreme western and eastern ends of the Mesabi range, it is apparent that the chief feature of the whole range consists in the agency of volcanoes in the production of the rock that carries the ore. N. H. W.

No. 847G. Muscovadyte. *(Fragment in gabbro.)*

S. W. ¼ N. W. ¼ sec. 6, T. 64-5. Island in Gabemichigama lake.
Ref. Annual Report, xxi, page 65; Annual Report, xv, pages 171, 172; Annual Report, xxiv, page 127; Final Report, v, page 905.

Meg. Gray, granular, fine grained.

Mic. Owing to the extreme importance of the characters of this rock in their bearing on the question of the origination of the gabbro, two additional thin sections were made. The rock is distinctly a typical granulitic gabbro, but some of the large *diallage* masses, having a common orientation throughout, surround granular *feldspars*; yet, usually, the diallages are in isolated, small, roundish grains lying between the feldspars, or breaking the margins of two contiguous feldspars. Rarely a small diallage is embraced within a feldspar. Two sections.

Age. Cabotian (changed Keewatin). N. H. W.

No. 837G. Greenwacke. *(Tuffaceous.)*

S. W. ¼ N. W. ¼ sec. 12, T. 65-5. Shore of Cucumber island in Sea Gull lake.
Ref. Annual Report, xxi, page 64; Annual Report, xxiv, page 124. Compare rock No. 597W, Annual Report, xvi, pages 297-299.

Meg. A light-greenish, much decayed rock, with numerous subangular included rock masses, which are of lighter or of darker color. The weathered surface carries a rusty film, which is in some cases a sixteenth of an inch in thickness, evidently produced by the oxidation of the rock itself. Apparently tuffaceous.

Mic. The slide is largely isotropic. The rather radial arrangement of some of the much-altered older crystals suggests an originally igneous massive rock, at least for portions of the rock. These older crystals appear to have been mainly *feldspars*, and they are now replaced principally by *calcite*, *chlorite*, and rarely in part by *biotite*, but they are occasionally partly preserved. The biotite is interleaved with chlorite. The general isotropic aspect is due to the dissemination of chlorite rather than to the present existence of tuffaceous glass. The rock may have been a microlitic zirkelyte, passing locally into a fragmental tuff. Two sections.

Age. Probably Lower Keewatin.

Remark. It is in the midst of such rock as this that occurs the segregated marble of Ogishke Muncie lake. The fresh red mineral mentioned by Dr. Grant (Twenty-fourth Annual Report, page 124) is calcite, effervescing rapidly in cold HCl. N. H. W.

No. 1030G. Granite *(with hornblende and biotite).*

Forms the barrier at the falls of Rainy river at Koochiching.
Ref. Annual Report, xxiii, pages 55, 221; American Geologist, vol. xx, pages 293-299, November, 1897.

Meg. Medium grained, with much biotite and hornblende, causing a dark speckled appearance, sometimes rather porphyritic. "It contains many dark masses, sometimes a foot or more in diameter; they are composed of the same minerals as the main part of the rock, but mica makes up a very large proportion of each dark mass." Specimens examined were taken from the excavation for a canal at Fort Frances, made by the Canadian government several years ago.

Mic. The following description is condensed from that of A. N. Winchell, published in the American Geologist (*loc. cit.*).

Orthoclase is quite abundant in irregular grains. They include biotite, apatite, quartz and hornblende, and occasionally show Carlsbad twinning, and micropegmatitic intergrowths.

Biotite also is abundant.

Andesine oligoclase is quite common. It is Carlsbaded, with albite twinning in both parts. No other plagioclase could be detected by the method of Fouqué.

Microcline occurs quite freely, embracing kaolin, epidote, quartz and biotite.

Hornblende appears rather sparingly, and sometimes shows zonal structure, with inclusions of other minerals.

Quartz is in irregular grains, with few inclusions, and occasionally as micropegmatitic growth in orthoclase and in andesine-oligoclase.

Epidote is abundant, frequently showing the crystal form, especially in the midst of biotite.

Kaolin is common in all of the feldspars, sometimes associated with secondary quartz and heterogeneous occurrences of epidote and sphene.

Apatite appears in needle-like forms and in short prisms, and sometimes is so thickly crowded in highly altered areas as to suggest a secondary origin.

Sphene is in small amount.

Tourmaline, in hexagonal crystal form and in shapeless aggregates, is identifiable in limited amount.

Pyrite is rare.

Calcite was unsatisfactorily identified in a few small grains.

Zoisite is about as abundant as apatite, and is distinguished from epidote, with which it is associated in origin and occurrence, by the smallness of its grains and its blue-gray interference color.

Muscovite was doubtfully distinguished.

By the use of a specific gravity liquid the constituent minerals were separated with the following approximate result:

Mica,	12	per cent.
Above 3.,	9.29	"
Between 3. and 2.661,	34.66	"
Between 2.661 and 2.642,	25.02	"
Between 2.642 and 2.58,	7.60	"
Below 2.58,	11.43	"
	100.00	per cent.

which warrants the following proportionate distribution of the minerals:

Biotite,	specific gravity 2.8 to 3.2,	12 per cent.
Muscovite(?),	" 2.75 to 3.2,	.....
	Above 3.,	9.29 "
Hornblende,	specific gravity 3.2 to 3.3,	.....
Epidote,	" 3.25 to 3.36,	.....
Zoisite(?),	" 3.25 to 3.36,	.....
Apatite,	" 3.16 to 3.22,	.....
Sphene,	" 3.3 to 3.7,	.....
Tourmaline,	" 3. to 3.24,	.....
Pyrite,	" 4.9 to 5.2,	.....
	3. to 2.661,	34.66 "
Calcite(?),	specific gravity 2.72,	.....
	2.661 to 2.642,	25.02 "
Andesine-Oligoclase,	spec. gravity 2.645,	.....
Quartz,	" 2.65,	.....
	2.642 to 2.58,	7.60 "
	Below 2.58,	11.43 "
Orthoclase,	specific gravity 2.54 to 2.56,	.....
Microcline,	" 2.56,	.....
Kaolin,	" 2.34 to 2.57,	.....
		100.00 per cent.

Hence, basing a calculation on the fairly accurate determination of the biotite, the minerals are approximately in the following proportions:

Orthoclase,	18.00
Andesine-Oligoclase,	16.00
Biotite,	12.00
Microcline,	12.00
Quartz,	12.00
Hornblende,	10.00
Epidote,	7.00
Kaolin,	5.00
Apatite,	4.00
Zoisite,	3.00
Sphene,	2.00
Tourmaline, pyrite, calcite and muscovite,	1.00
	100.00

The anomalous mineral figured by the author of the foregoing description appears to be a twinned hornblende with two central remnants of pyroxene. The hornblendic zones, surrounding the nuclei of pyroxene, embrace micro-poikilitically several grains of quartz oriented uniformly with the adjacent quartzes, but no inclusions are in the pyroxenic cores, except that about their margins hornblendic spurs crowd upon their boundaries. The hornblende seems to have been formed from two original augites whose cleavage and orientation do not agree either with each other or with the surrounding hornblende.

The confused aggregates above called kaolin are more likely to be of the nature of rejected but recrystallized substances embraced in the regenerated feldspars after complete metamorphism, consisting partly of mica and in part probably of fine-grained epidote. There is nothing in the rock that can be correctly attributed to decay since its final consolidation. Three sections.

Age. Archean. N. H. W.

No. 433H. Flint. (*Taconitic.*)

Gunflint lake, north shore, a few rods west of the entrance of a small creek which flows into the lake from the north just north of the mouth of the Boundary (Gunflint) river, about an eighth of a mile up the creek. This rock appears to be vertically bedded, and when collected was supposed to belong to the Keewatin.

Ref. Annual Report, xvii, page 104. This rock is of the same character as No. 1277, which occurs at the lake shore and lies nearly horizontal.

Meg. Black or greenish black, fine as flint, with conchoidal fracture, frequently jointed, but with a band of coarser grain running like a sedimentary layer through the middle, parallel with the sides. Petrographically this grades into rock No. 436H, below.

Mic. Plainly taconitic. The interstices between the globules are completely filled with the usual quartz mosaic, but the globules are only partly so occupied. Some are wholly replaced by quartz, but the majority are still rather amorphous or are crowded with dirty impurities through which, between crossed nicols, but faint light can be seen to pass. It is yellowish, and distributed in a mosaic fashion throughout the globules, showing probably the initial establishment of the same quartzose background. In other globules the circumferential iron rim is conspicuous, though rarely entire. The globules are all subangular, some are club-shaped, and some are crescentic. The intraglobular quartz mosaic is finer than the interglobular. Plate v, figure 10. One section.

Age. Animikie; iron-bearing (flinty) member.

Remark. There is a notable difference in the appearance of the different globules, as to coarseness and completeness of silicification, as well as between the matrix and all the globules. These contrasts can be explained by supposing that the sand itself was not a homogeneous substance, but contained grains of silicified rhyolyte as well as non-silicified, and that the oceanic precipitation of silica formed a coarser matrix which embraced them all alike. N. H. W.

No. 436H. Conglomerate. (*Taconitic.*)

Near the same place as the last, but about an eighth of a mile further up the same creek. Here the creek spreads out into a marshy lake. At the head of rapid water on the east side of the stream are thick beds of horizontal Animikie of the nature of a somewhat decomposed, fine, dark conglomerate, some of the pebbles, however, being about an inch long, but flattened horizontally. This conglomerate is unquestionably the same as rock No. 1294.

Ref. Annual Report, xvii, page 104.

Meg. A rusty conglomerate, but cemented by quartz, becoming finer and grit-like.

Mic. This is simply a coarse phase of the taconyte of the Animikie. It presents nearly every aspect mentioned under Nos. 1294 and 1530, and in addition has the character of being a conglomerate. One section.

Age. Animikie.

Remark. It is evident that these pebbles, when they were gathered into these conglomeratic beds, must have been harder than ordinary glauconite, and that they had an abundant source of supply. It is also evident that, in part at least, they were already silicified. They must have been derived from rhyolytes more or less silicified (or jaspilytes) which previously covered the Archean, and which can be seen lying on the Archean at the west end of Gunflint lake, at the east side of Black Fly bay.

Taken together the sections of rocks Nos. 1689, 433H and 436H afford an important demonstration, viz.: That in one direction the rock taconyte grades into a fine black flint, and in the opposite direction into a conglomerate in which the globular masses increase to pebbles over an inch in diameter. This shows that these rocks had the same source, as the microscope shows that they have the same composition.

N. H. W.

ROCK OF AGES.
Viewed 2½ miles from the North.