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THE KEWEENAW SERIES OF MICHIGAN

BY
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LETTER OF TRANSMITTAL.

Lansing, Mich., Nov. 1, 1911.

To the Honorable, the Board of Geological and Biological Survey of the State of Michigan:

Gov. Chase S. Osborn, President.
Hon. D. M. Perry, Jr., Vice President.
Hon. L. L. Wright, Secretary.

Gentlemen—I have the honor to transmit for publication as a part of the report for 1909 of the Board of Geological and Biological Survey, Publication 6, Geological Series 4, in two volumes, a contribution to the geological survey of the State.

Very respectfully,
R. C. ALLEN,
Director.

FOREWORD.

May I take the opportunity to express my obligations to Mr. A. H. Meuche for help rendered since he left the Survey and to Mr. R. C. Allen, my successor as State Geologist of Michigan, as well as to all those who both on and off the Survey have done so much to help me. I want to thank Mr. Allen in particular for aid in finishing up the illustrations, as well as for his willingness to help me in every way, and especially for permission to announce that while the cross-sections are on a rather small scale, engineers who have need of them on the original scale can make arrangements with the Survey office to obtain blue prints.

It is one of the necessary inconveniences of publishing that by the time a thing is out, it is out of date. I regret that I have not been able to give to the able work of Van Hise and Leith in Monograph 52 of the U. S. G. S. (the report on the geology of the Lake Superior region) the attention which it deserves. The text of this report (part of that for the year 1909, it will be noted) was written before that appeared. I have inserted a few necessary references in the foot-notes, while reading proof, mainly to indicate points where our views diverge. But I have not thought I ought to burden an already bulky report by augmentation. I am glad to say we now practically agree as to the stratigraphy of the Keweenawan and other *facts*, and these will, in due time, speak for themselves.

Very respectfully,
ALFRED C. LANE.

CHAPTER I. A POPULAR DESCRIPTION.

§ 1. INTRODUCTION.

This first chapter is intended to be a short account of the whole subject put in language that may be understood by people who have taken no course in geology. It is based on an article for the Lake Superior Mining Institute, but I have tried to fit it for an even wider circle of readers,—the miner, the normal school student, and the business man. And I have tried at the same time to convey as much information as possible. In such a chapter the arguments for the various conclusions can not be given and it must be largely a statement of results, for the results may have to be derived from the most refined and technical research.

In my studies of the copper bearing rocks I have received favors from mining men from one end of the range to the other and I take occasion here to express my thanks to C. A. Wright, W. W. Stockly and A. H. Sawyer of the Keweenaw Copper Co., W. J. Penhallegon, who took a very intelligent interest in the matters over which he had charge for the Calumet and Hecla around the Delaware; D. D. Scott at the Phoenx; Dr. L. L. Hubbard, my friend and co-worker in science, and A. Formis who have charge of the Ojibway; Fred Smith and W. F. Hartman at the Mohawk and Wolverine; Capt. James S. Chynoweth; Jas. McNaughton and E. S. Grierson, F. W. Ridley, G. H. Heath, J. B. Cooper, J. Pollard, and many others at the Calumet; R. M. Edwards, Mat. M. Dennis, Charles B. Lawton, R, H. Shields, A. C. Burrage, Norman W. Haire, W. J. Uren, Jas. E. Richards, F. W. Denton, R. R, Seeber, Reg. C. Pryor, Mr. Hotchkiss, of the Adventure, J. M. Wilcox, E, Fenner Douglas, Geo. Hooper, and R. S. Schultz.

§ 2. THE LAKE SUPERIOR BASIN.

The State of Michigan is divided by Lake Michigan into two peninsulas (Fig. 1), winch may be likened to the right and left hands of the State. In fact the resemblance is so striking that the district east of Saginaw Bay has long been known as the Thumb of the Lower Peninsula. But just as the Lower Peninsula lies between Lakes Michigan and Huron with Point Aux Barques projecting as a thumb into Lake Huron, so the Upper Peninsula lies between Lakes Michigan and Superior (Fig. 1). Upon this point occur the famous mines of native copper, which may perhaps be classed as the richest and the deepest in the world. The rocks in which they occur surround Lake Superior continuously at the west end and patches are found at intervals all around it. They consist mainly of alternate layers of reddish sandstones and pebble beds, that is, conglomerates and layers of once molten lavas known as felsite, trap and amygdaloid. These beds dip toward the lake from all sides and individual beds can be shown to dip down, pass beneath it, and re-appear on the other side.

Lake Superior is about 412 miles long, and has an area of 31,200 square miles. The greatest depth is 1,008 feet and most of the lake is over 500 feet deep. Its average breadth is about 76 miles and since its depth is from one to two-tenths of a mile, it can be shown that it is a real, though slight, concavity in the round of the earth's surface, for the curvature of the round earth, in a distance of 80 miles would mean that the level curve of the water would be about one-tenth of a mile above a straight line drawn from side to side. Thus the downward curve of the bottom of the Lake Superior basin is greater than the natural upward curve of the water surface. But if the bottom of Lake Superior is a downward curve, much more so must be the earth's crust passing beneath it. It is important to remember this, for if a downward bend is formed in the earth's crust it will not be easy to reverse it, any more than it is easy to reverse a crease in a piece of paper. So we are not surprised to find that the Lake Superior region seems to have remained a basin (or synclinal) from away back in geological history.

Figure 1. Outline map of Michigan showing the "Thumbs;" also the mean annual temperatures. See Chapter VI, § 2.

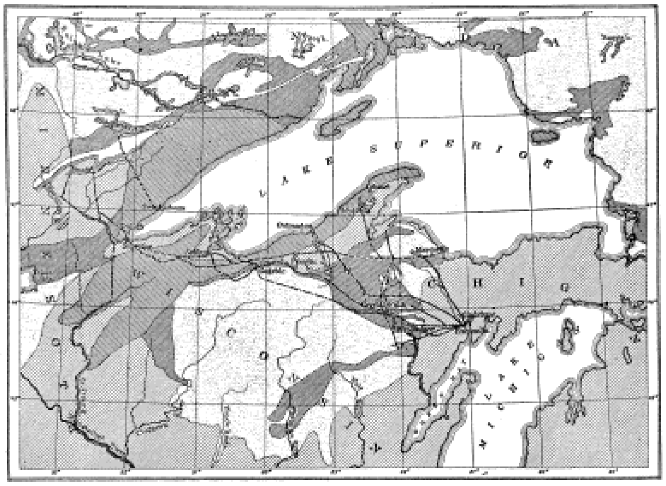

Figure 2. Lake Superior region. Stippled areas are perhaps Pre-Huronian, those heavily lined down to the left are Huronian, down to the right are Keweenawan; Post Keweenawan is lightly lined down to the left. After Macco, Zeitschrift for praktische Geologie, 1904, p. 379.

Accordingly, the beds to the northwest of the Lake dip to the southeast, and those to the south dip northward.

On the north and on the south of this basin-shaped (synclinal) downbend, are upbends, bosses, shields or anticlinals, as they have been called. These upbends have largely been worn away, exposing cores of granite. This granite appears south of Bessemer and Ironwood, and again in the Huron mountains. Intermixed and around these cores of granite come first a series of dark green rocks, in which the mineral hornblende is very conspicuous. These are the Keewatin rocks.

Next come the series of Huronian rocks in which our Michigan iron mines are located (Fig. 4). Like the Keweenawan rocks, the Huronian rocks on the north and south sides of Lake Superior are similar. For instance the Iron Range of Gogebic Lake corresponds to rocks about Port Arthur. Overlapping these there is a fringe of the copper bearing or Keweenawan rocks, which on the south side of Lake Superior are exposed at intervals from Silver mountain, which lies south of the head (of Keweenaw Bay, past the south end of Lake Gogebic. On the north side they are found along the north shore of Lake Superior from Duluth to beyond Port Arthur. The succession of rocks is given in more detail in Figure 4, and is described in a later chapter.

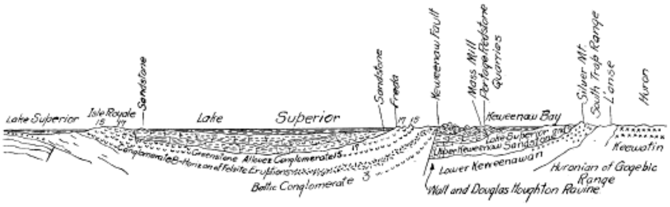

Figure 3. Cross section through Lake Superior from the Huron Mountains to Port Arthur. After Mines and Minerals.

§ 3. THE KEWEENAW FAULT.

The center of this basin has been crowded out of place and lifted up. Blow contraction of the earth causing compression of the outer layer of the crust may have produced such a stress as to spring it up (Fig. 5a), or it may have been lifted up on the back of some vast sill of molten rock thrusting its way in beneath (Fig. 5b). Such, a great inserted mass (batholite) of heavy rock (gabbro) forms the basal member of the Keweenawan series in Minnesota and in Michigan near the Bessemer poor farm[1] is a similar basal intrusive sheet of gabbro. The latter is not so well exposed as the one in Minnesota. The lines of fracture along which beds have been thus displaced are known as faults (F'F of Figure 5). Faults are not really straight although they are generally drawn as straight lines, nor are they always inclined at the same angle at every point. Though at times they are marked at the surface by a single narrow line which may be followed by a narrow seam of red clay, known to miners as fluccan, they are frequently characterized by a broad belt of shattered rock.

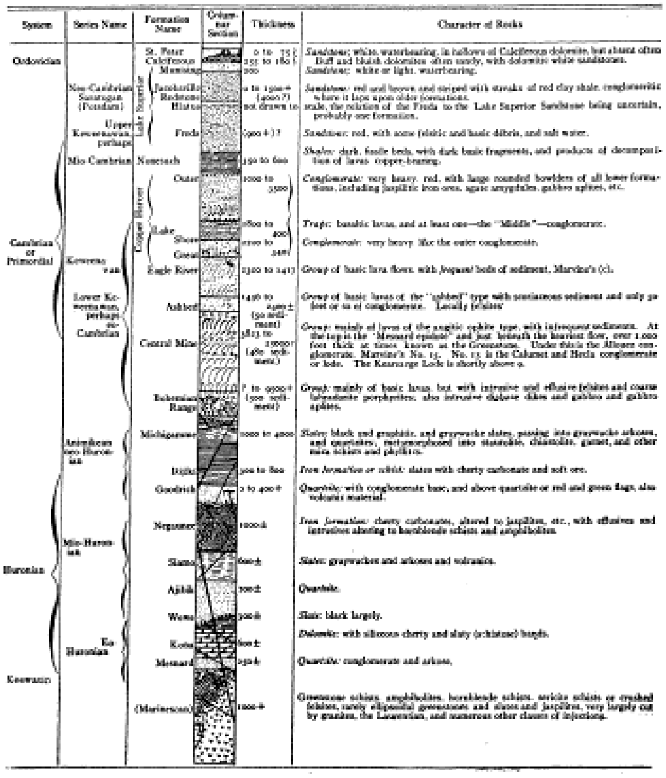

Figure 4. Geological Column about Lake Superior. After Journal of Geology, and Fig. 2. Report for 1908.

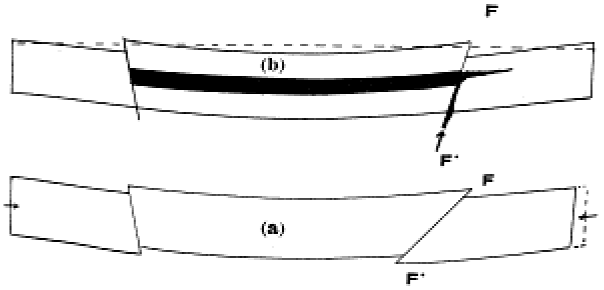

Figure 5. Figures illustrating two possible explanations of the Keweenaw Fault, the lower (a) formation by compression; the upper (bL formation by the intrusion of a great gabbro sill.

The great crack or fault in Michigan runs from Bete Gris Bay on Keweenaw Point southwestward past the north end of Lake Gogebic.

Thus going west from the Huron mountains we pass over flat lying sandstone (the Jacobsville sandstone) around the head of Keweenaw Bay, at Baraga, and near the Mass mill, which belongs above the copper bearing rock. Then we come to a great fault, on the northwest side of which the country is higher and the rocks are uptilted so as to bring lower rocks, the copper bearing rocks, into view. These beds dip at first steeply, then more gradually northward to the lake. They are matched on the other side by similar beds on Isle Royale, which have steep dips with felsite at the north margin of the island as Keweenaw Point has on its south margin. The backbone of Isle Royale and that of Keweenaw Point is the same lava flow. The former is fringed on the south side by sandstone, while on Keweenaw Point sandstones occur near the various mill sites at Freda.

One reason for thinking that this great fault which bounds the copper range on the south is not merely due to intrusion, but in part to some long, slow action, like the shrinkage of the earth, is that there seems to have been motion along it for ages. Not so very far from it at Limestone mountain (in Sections 23 and 24, T. 51 N., R. 35 W., and again in Section 7 northeast) Paleozoic strata as late as the Niagara are caught and preserved in a fold in the Lake Superior sandstone, which along the line of the fault is disturbed from its normally nearly horizontal position. A picturesque instance of this is the Wall ravine not far north of Lake Linden, which, as well as the more noted Douglass Houghton ravine and falls, is north of and close to the electric line from Calumet to Lake Linden. A mile or two south of the College of Mines a number of ravines also show the fault, and the same region shows indications of faulting before as well as after the deposition of the Lake Superior sandstone, in the overlap of this sandstone upon the upturned copper range. Pebbles of lower beds of the Keweenawan series are also found in the higher conglomerates of the same formation, showing that the uplift began in Keweenawan time, and yet the fault line must have been a center of disturbance ages later.

Such a line of weakness when once formed naturally remains a line of weakness. Hobbs has shown that earthquakes follow the same lines of weakness again and again.

There is another way of looking at the faulting. The Keweenaw and previous formations show great overflows of molten rock from the earth's interior. The granite areas of the Huron mountains show great dikes of these lavas which have been thrust in and congealed. We therefore may easily see that if the lavas came from beneath Lake Superior there would be a tendency for the crust above to slump and perhaps for the sides to come together to fill the void thus left.

There are other main faults like the Keweenawan fault, notably one on the south side of the Porcupine mountain range, and others described by Lawson around Port Arthur.

§ 4. OTHER CRACKING.

With this uplift naturally came a good deal of other fracturing of the rock, splinter faults we might call them, and all this disturbance may have had a good deal to do with setting up and guiding the circulation of the waters that laid down the copper. Some people think that the copper was introduced into the formations at this time, but the writer thinks that it was only collected together into workable deposits.

The amount of uplift differs in various places and in some of them rather suddenly. While around the Calumet mine the beds dip 41 degrees or less, in the vicinity of Hancock and Houghton the dip is nearer 56 degrees, and a few miles farther south in the mines of the Copper Range Co. on the Baltic lode it is about 70 degrees. Numerous data on dip will be found in Chapter V.

There are many fractures running across the formation. The following figure shows a few of those along the Gogebic range, and how the range is by them broken up into blocks.

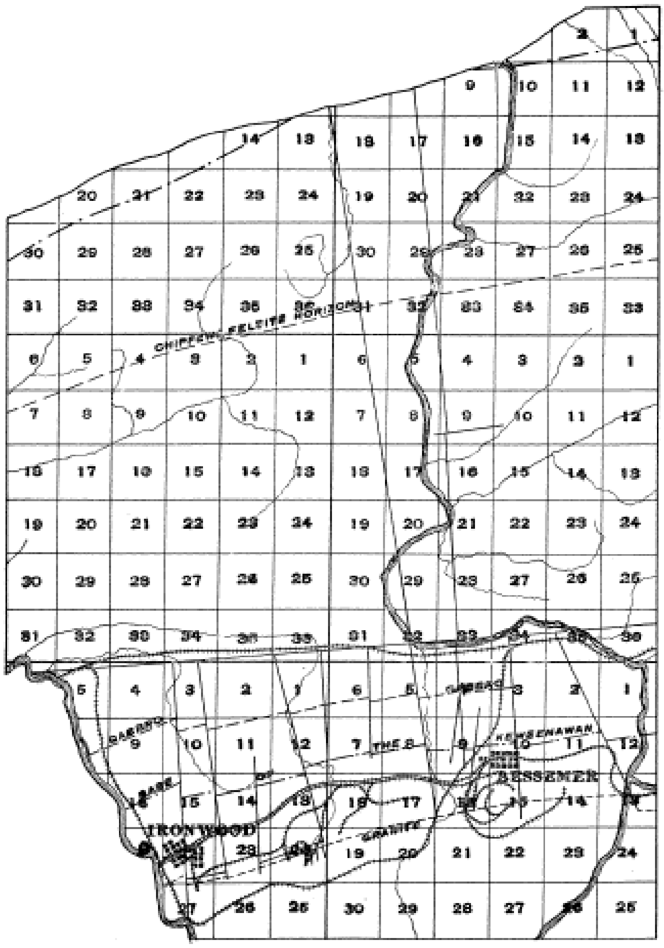

Figure 6. Cross-fractures north of the Gogebic Range. (From Report for 1906, Fig. 24.)

Further references to these fractures will be found on consulting the index. See, for instance, the fractures on the Wyoming and Manitou properties. Sometimes the beds are only slightly displaced and the fracture is marked merely by a seam in many instances filled with some white mineral like calcite or quartz. The pinkish sawdust-like laumontite, the lead colored copper ore, chalcocite (or glance), native copper, and brass colored copper arsenides like Mohawkite occur in the seams. Along some fractures the displacement is greater but in most instances it is only a short distance. Hardly a mine is without cross-fissures, yet it can not be said that in general the mines are richer next to them in the main Keweenaw range.

Usually, but not always, at a fissure running northward a bed running, or as it is called, striking east or northeast and dipping north under the lake is found to the right as

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[1] Annual report for 1906, p. 488.

one follows it across the fissure from west to northeast or east, as though the beds had on that side been thrown to the south or downward. This is well marked in the last two fissures of Figure 6. However, in following a bed across what seems on the surface to be such a fracture the bed may never be lost entirely but simply deflected suddenly from its course on entering a belt of much disturbed ground, filled with innumerable minor fractures coated with clay called clay seams. Such a belt may be called a shear zone or kink in the formation (Fig. 11) as though some gigantic pair of shears had started to cut the formation apart and make a fault, but had stopped in the act.

Some of the beds of the copper bearing (Keweenawan) series are copper bearing for long distances,—so-called bedded lodes. The Kearsarge lode, so-called, is being mined from the La Salle, the south line of T. 56 N., R. 33 W., to the Ojibway, Section 14, T. 57 N., R. 32 W., that is 13 miles, and it is known to bear copper in paying quantities, at least in hand specimens, for twice this distance.

Now when such bedded lodes are crossed by fractures a change in their productiveness occurs. This will be gone into more fully in a chapter on the distribution of copper. Toward the end of Keweenaw Point, where the dips of the beds are relatively flat in the upper part of the formation, the cross-fissures were the first and most extensively mined and the bedded lodes are richer near them. Near Portage Lake the reverse seems quite as often true.

§ 5. SLIDES.

Fractures running across the formation are by no means the only ones which are present. If we bend up a pack of cards we notice a good deal of slipping of one card over the other. Unquestionably there has been much slipping of one bed over another in the up tilting or bending of the Keweenawan beds. Sometimes this is shown by a polishing of the two different beds adjacent to the contact line, "slicken-sliding" it is called. The polish is not perfect and the direction of motion is indicated by scratches. Some-limes one or both of the beds lying next to such a slide are shattered with small fractures or rubbed down to a red clay called fluccan.

But probably more often than it is easy to prove these slides do not run at all times exactly with the beds but dip more steeply.[2]

All these fractures parallel to the strike of the beds are liable to be called slides as well as veins. If, however, we assume that when these faults are not parallel to the bedding they dip more steeply, such faults, if they do not produce repetition of the same bed; but strike out a part of the series, must be really slides, or as it is called "normal," as shown by the following figure (7).

By studying Figure 7 one can see that shafts or drill holes might" miss the conglomerate entirely or seem to find the bed beneath abnormally thin owing to a downward displacement of the bulk of the strata (bed d-e). Now, as a matter of fact, in matching the records in various shafts, drill holes and cross-cuts it much more often seems as though something was gone, than as though some set of beds were repeated. For instance the well-known "slide" under the Greenstone often seems to have wiped out of existence the Allouez conglomerate. The Kearsarge conglomerate appeared at the bottom of the Central mine, but was wiped out in higher levels.[3] Another slide has in many places reduced the Wolverine sandstone to a mere remnant. It is easy to ascertain when a well-known conglomerate is gone, but not so easy to ascertain that a trap bed is merely reduced in thickness.

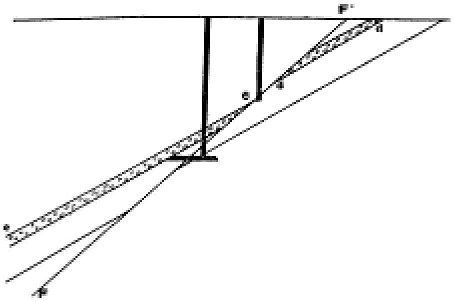

Figure 7. Illustrating effect of normal slide faulting.

§ 6. CHARACTER OF THE BEDS.

The commonest copper bearing rocks are mainly old lava flows, and the usual type is much the same as any ordinary trap or basalt. The amount of silica in the trap rock is about 46 per cent, alumina 1.5 per cent, iron oxide 13 per cent, lime to 10 per cent, magnesia, say 7 per cent, soda 3 per cent, and not over 1 per cent or 2 per cent each of carbon dioxide, combined water, titanic oxide and potash. Other ingredients are present in only a small fraction of one per cent. The composition as a slag would then be not far from the following:

$(CaO)\ (MgO)\ (Na_2O\ FeO)\ (FeAl)_2O_3,\ 4(SiO_2)$.

This would be nearly the composition of the mineral known as augite, but in such a rock there would be only 25 per cent to 30 per cent of augite, a little over half would be a lime soda feldspar and the balance would be magnetite or ilmenite, chrysolite (olivine) and chlorite, zeolites and other minerals usually called secondary. Such a rock, if so coarse that both feldspar and augite can be recognized, would be in Pirsson's and Chamberlain and Salisbury's field classification, a *gabbro*—if less coarse, so that while the constituent feldspar is plainly observable the dark mineral can not

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[2] A very well known illustration of the kind occurs in the Michigan mine (formerly Minesota with one n) in which the "North" vein which dipped 52° to 64° came down on a conglomerate which dipped about 44°, the two intersecting at the 40-fathom to 60-fathom levels, where the greatest masses of copper ever found were located, as described by Lawton in the report of the Commissioner of Mineral Statistics, 1880, p. 76. A mass weighing about 500 tons, 46 feet long, 181/2 feet broad, 81/2 feet thick, average breadth 121/2 feet, average thickness 4 feet, was the largest.

[3] See Lake Superior Mining Institute, 1895, Plate IV.

be made out (and good geologists have indeed often mistaken augite for hornblende in these rocks), a *dolerite*, while if finer yet it would be, if not porphyritic, a *basalt*, if porphyritic, a *melaphyre*. All these varieties *may* occur in one and the same lava flow, and it is convenient to have some term to apply to a lava flow as a whole regardless of its varying coarseness of grain. We might call these flows *traps*, but time-honored usage in Lake Superior discriminates the main massive part as *trap* from the originally porous upper part as *amygdaloid*. These are semi-popular terms.

The term *gabbro* is kept for the deeper-seated intrusions. Most of those rocks which are generally fairly uniformly coarse in grain are *gabbro.* All the effusives are wholly or partly of the melaphyre type. So we continue to use the term *melaphyre* for the dark colored lavas generally, and call the coarser streaks *doleritic melaphyre*, instead of *dolerite*.

Since many writers confine the term basalt to younger, more vitreous rocks and very many apply it to porphyritic rocks, and since this term has not been much used in connection with these Keweenawan rocks, the term melaphyre being used by Pumpelly, Irving and most writers, we shall not introduce it here, but continue to speak of melaphyre, feldspathic melaphyre;, and luster mottled melaphyre, or ophite. The chemical character of these rocks is the subject of a separate chapter and has recently been quite fully discussed by A. Winchell. Variations in composition arise in these rocks from increase in silica or soda and decrease in lime when compared with the prevailing types. In either case the rock is liable to be relatively finer grained considering its thickness. As the soda increases and the lime diminishes we find a strong tendency for the feldspar to have crystallized out earlier and occur clotted together (or glomeroporphyritic) in lighter angular light greenish or reddish forms on the porcelain-like mass of the rock. Such crystals are called porphyritic crystals (phenocrysts). Large porphyritic crystals are characteristic of certain beds, the foot of the Kearsarge lode, for instance, and the Ashbed melaphyres.

As the silica increases there is a strong tendency to flesh, red, and light colors, and the occurrence of phenocrysts of white feldspar, or of quartz either round or nearly square. If the quartz particles are inconspicuous the rock is called felsite, if conspicuous quartz porphyry, or as has been suggested quartzophyre.

These traps are mainly surface lava flows or sheets, like those that fill the Snake River Valley in the west, and cap so many mesas, and line the flasks of volcanoes like Vesuvius, Etna and Kilaüea.

The top of each flow is naturally more likely to be open in texture, full of bubbles, and thus more porous and easily crushed. Such tops are known as amygdaloids, and they are sought by the explorer, for in the filling of their pores the copper may be concentrated. A real amygdaloid top to an independent lava flow is likely to be fairly persistent and has numerous round walled cavities often filled with some white mineral. Its top is commonly pretty well marked while its base fades out gradually into the underlying not bubbly compact part of the flow which is distinguished as "trap."

But just as modern lavas or streams of slag are liable to gush over and envelope cooled crusts, or crystallize and leave cavities like those lined with melilite crystals in the pots of slag from the copper cupola furnaces, so was it with these old lavas. Amygdaloidal streaks often run down into the trap,, and amygdaloid spots, bombs, or inclusions, characteristic under the Wolverine sandstone, are often found in the solid trap, and coarsely and openly crystallized "doleritic"[4] streaks are also found especially in very thick flows, and between the crystals, calcite, etc., may form giving these streaks also a spotted and amygdaloidal appearance.

The trap under the amygdaloid, the foot wall trap, is liable to be relatively lighter and more feldspathic, feldspar being the lighter mineral. The feldspar is generally oligoclase or labradorite, and appears as rice-like grains if the. rock is coarse enough. The darker interstitial matter is mainly augite or its alteration product, chlorite. The olivine is easiest recognized when it is more or less changed to a reddish micaceous mineral. The magnetite is not conspicuous in the hand specimen, but is easily attracted from the powder by a magnet. The hanging wall trap is generally darker and more augitic.

If the rock is very feldspathic and the feldspar is oligoclase there is a strong tendency for the feldspar to crystallize out early, either in sharp crystals or in groups of crystals which, where somewhat decomposed, are quite easily mistaken, especially in the uncertain light of the mine, for the white filled amygdules. Such traps are particularly conspicuous above the "Greenstone" at about the horizon of the Ashbed.

At other times as we have said large crystals of labradorite feldspar are characteristic of a flow. This is true of the big trap whose amygdaloid top is the Kearsarge amygdaloid. When the flows are very feldspathic or siliceous the grain tends to be fine, the fracture conchoidal, the ring clear. When the flows are very augitic the feldspar laths are imbedded in the augite and the olivine and magnetite are crowded between the augite patches. These augite grains increase in size from the base of the flow toward the center. The increase is not absolutely regular and depends on the composition and other circumstances as well, but very commonly the diameter is 2 to 3 ten-thousandths of the distance from the margin.[5] These rocks Pumpelly very graphically called luster mottled melaphyres, since a freshly broken piece held in the light shows lustrous mottlings here and there from the cleavage faces of the augite, which appear as patches interrupted by the enclosed feldspar. The fracture of such rocks is rough and hackly or bubbly, not smooth and conchoidal like porcelain or glass.

On a weather beaten surface the augite centers seem more resistant than the interstices which give the pock-marked appearance that caused the rock to be called in Poster and Whitney's time, Varioloid greenstone.[6] This occurs in *various* beds, but shows up beautifully in the great ridge locally known as the "Greenstone" on Isle Royale (Plate I),[7] at Monument Rock, and elsewhere, and on the crest of the ridge that rises above the Cliff, Phoenix, Central and other old mines of Keweenaw Point. I owe to Mr. W. J. Penhallegon a number of good views. (Plate II.) This rock may finally break down to a coarse gravel, the size of the particles of which is determined by the fact that many of the fragments are single augite crystals or a good part of them.

The same structure comes out, though very faintly, in color patterns, even on rather fresh specimens, in faint shades of purplish brown and green. With a little more weathering, the same structure may be brought out in shades of yellow and brown, especially on the smooth "joint" planes by which the rock is often riven. On smooth, but not polished, surfaces such as beach pebbles or diamond drill cores, the pattern is brought out better than on polished surfaces. The structure is of course obvious in thin sections. Many of these patterns resemble the mottling of a reptile's (ophidian's) back, as shown by Plate IV, and for this reason many French writers have called this texture ophitic and rocks which exhibit it, ophites, a term which I have adopted for our luster mottled melaphyre.

In intrusives the gases do mot escape and the crystallization of the feldspar is promoted and the termination thereof delayed, so that it is much coarser relative to the augite and at the same time less sharply embedded in an augite matrix. In addition to the lavas are sediments which are derived from them. On Keweenaw Point there is almost no material that may not be derived from the series itself, and much of it is, as Marvine has pointed out, extremely local. But the Keweenawan conglomerates, contain many pebbles of Pre-Cambrian granites and greenstones, and the Keweenawan north of the Gogebic range also contains pebbles of the iron bearing formations to the south.

The sediments are generally red, maroon or purple and they vary from very coarse conglomerates with huge pebbles many inches in diameter to fine red mudstones. These latter often show beautiful sand ripples and mud cracks, and sometimes have curious markings suggestive of soft worm tracks (See Plate V).

The shales and fine grained rocks are rarely black. The most conspicuous case of this is the Nonesuch shale horizon which will be described later. But a few other cases occur, for instance, a bed in the Rockland district (21, Adventure section, chapter 5, § 25). Such black shales, however, seem not to be bituminous, but to owe their black color to the fact that they are made up so largely of dark particles of the trap-like serpentine. This is shown in an analysis by Dr. Gysander of the Cochrane Chemical Co., made with extra care for us. (See § 16. TABLES OF ANALYSES AND NOTES.) It Will be seen that there is practically no chance for carbon, but that the black color is due to a composition which may be accounted for by the addition of ground-up trap from which the lime has been abstracted. It is practically a black sand like those along Lake Superior. The presence of palladium, a rare and valuable mineral of the platinum group, such as are found in the Oregon black sands, is very suggestive. The sample was taken from a drill core as far as possible from any known vein or lode though to be sure in the course of drilling up the Nonesuch. A corresponding variety occurs among the conglomerates, those that I am now calling *amygdaloid conglomerates* because they have many amygdaloid pebbles in them. I have also called them *scoriaceous conglomerates*, but the former name reminds one of the fact that they look a good deal like amygdaloid and at the base run into scoriaceous amygdaloid. They have been called *ashbeds*. But the real volcanic ashbeds, like the Mesnard "epidote,"[8] are puzzling fine grained beds. *Clinker beds* would be a better term for these rocks. Moreover, in genuine volcanic bombs and scoria there is a variation in texture from the margin to the center. This is sometimes the case in these conglomerates but not always. We need a term to include all those beds which are characterized by a red shaly cement, matrix or base in which are pebbles of the traps. The red sandy and shaly matter also works into the loose clinkery top of the lava and makes scoriaceous amygdaloid, and it is often impossible to tell where the base of one of these amygdaloid conglomerates is, especially in drill cores. In fact this red shaly or sandy sediment may work far down into the old lava beds or traps, following the cracks that formed as it cooled, and to such little red sediment-like veins I have applied Wadsworth's name of clasolite.[9] *Clasolites* are generally red or gray or epidote yellow-green, and to all intents and purposes the same as the matrix or filling in the amygdaloid conglomerates. Such shales may also be caught up by the lava in its flow.

A conglomerate may change from a conglomerate of red felsite pebbles to an amygdaloid conglomerate in a, very short distance. The Calumet and Hecla conglomerate, only a few miles south of the Franklin Junior, as Hubbard showed, and even nearer, is an amygdaloid conglomerate. One feature of all of the conglomerates, especially the smaller and lower beds is worthy of attention. Not only is the material largely derived locally from the formation itself, but it is only slightly rounded. This is notably the case in the Calumet and Hecla conglomerate itself which has accordingly been described as a *breccia*,—a term which it is convenient to reserve rather for angular aggregates made by the breaking up of the beds by disturbances.

This angular character of the pebbles is naturally to be accounted for by the fact that they seem in many cases to have been transported only a short distance. For instance, the quartz porphyry pebbles of Calumet seem to have come from a quartz porphyry only three miles away. Such facts would be explained naturally by supposing that the conglomerates are land formations, and in fact red colors are supposed to be often a characteristic of land formations. A deposit of red desert sand, wind blown or washed in by occasional floods, would be altogether natural on the tops of old clinkery lava flows, and it is easy to see how such amygdaloid conglomerates would form. In many of these amygdaloid conglomerates, there is a sharp break in character between the very fine sandy matrix (which looks much like the dust and sand I collected on mesas out west), and the pebbles or scoria which on the whole can be easiest explained in some such way.

Another fact that would suggest that some of these conglomerates were formed on a land surface rather than as marine deposits is the fact that thin beds are found to be persistent above and below lava beds that vary enormously in thickness. An illustration of this is the two conglomerates (Marvine's 15 and 16), one just below the other, not far above the "Greenstone," which thickens from less than a hundred feet near Portage Lake to probably over a thousand out on Keweenaw Point. The distance between the two conglomerates, 15 and 16, each of which is supposed to be continuous, increases in the same way. The most natural explanation supposes that the two conglomerates were old land surface formations, though this is not the only explanation.

That the felsites should weather into a mass of angular fragments, a cross between a conglomerate and a breccia, is entirely in accordance with their usual habit of weathering.

The writer is therefore now inclined to consider the Keweenawan as more largely a land surface formation than he did in writing his paper on Mine Waters for the Lake Superior Mining Institute in 1908. In this his views have been modified by discussion with Huntington, Barrell and Leith, quite as much as by his own widening experience. This does not by any means imply that many of the conglomerates were not laid down in standing water and others by running water, for they certainly were, but that one must be very cautious in assuming that they were laid down in sea water, though they may have been laid down in lakes.[10]

§ 7. GENERAL SUCCESSION OF KEWEENAWAN ROCKS.

(1.) *Lowest rocks. Bohemian Range Group*. When work was gun on the Black River cross-section northward from near Bessemer on the Gogebic range, the writer expected that the traps of the South Copper range, which extend from the south end of Lake Gogebic to this place, would prove to be a repetition of some part of the main range coming down from Keweenaw Point and lying north of the Duluth, South Shore and Atlantic R. R..[11] This cannot be made out.

The traps from Bessemer to North Bessemer appear to be older than any beds exposed north. While there are many flows of ordinary character, there are also beds with very conspicuous porphyritic feldspar, something like those below the Kearsarge lode, but more slender. The trap itself is peculiarly blue-black and fine. Quartz and agate amygdules, sometimes of good size, are common. Elongate, so-called pipe, amygdules also occur. Intrusive diabase dikes, near the Bessemer poor farm an intrusive tongue of coarse gabbro, and near the top of the series a genuine feldspar porphyry capped by an angular conglomerate of felsitic breccia combine to give this part of the series a peculiar type. To be sure, high up in the series the Chippewa felsite and associated rocks of the Porcupine mountains have certain points of resemblance to these, but there are a number of dissimilarities such that I can not take them to be the same.

A somewhat similar series of beds also forming the base of the visible series has been carefully described by Dr. Hubbard from the Bare Hills and the mouth of the Montreal river and the south slopes of Mt. Houghton and Mt. Bohemia. The uppermost layer is what Hubbard calls the Mt. Bohemia conglomerate, and up to this horizon occur effusive and intrusive felsites. The Mt. Bohemia gabbro cuts nearly up to this horizon, and may be younger. We may call this the Bohemian Range group. North of Bessemer the thickness seems to be 9,500 feet, but there are probably not over 500 feet of sediment.

The presence of this group between Calumet and Portage Lake and farther south along the range has been an uncertain question. Hubbard made out a strong case for the identity of the Bohemia conglomerate and the so-called St. Louis conglomerate on Section 30, T. 56 N., R. 32 W., and Section 35, T. 57 N., R. 32 W., but that was as far .as we have dared carry it with any assurance. The Torch Lake section given later has convinced me that the general horizon of the Bohemia conglomerate is that of Marvine's Conglomerate 8, exposed just back of the Arcadian and Isle Royale workings.[12]

Conglomerate 8, the top of this group, we assume, passes a few hundred feet below the Arcadian, Isle Royale and Winona lodes, which appear to be practically identical and may be the same as the first conglomerate south of the bluffs at the Lake, Mass, and Adventure

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[4] Vol. VI., Part I., Pl. 6, Fig. 3 and p. 167. I think the feldspar crystallizes better in the presence of steam, and that these doleritic streaks are where the lava had more water vapor.

[5] Two to three mm. in 10 meters or yards, or at the rate of 1 inch diameter between 250 and 400 feet from the margin.

[6] House Ex. Doc. No. 69, 31st Congress, 1st Session, 1850, p. 64.

[7] Pl. VII, of Vol. VI, Pt. 1, see also Pl. VIII.

[8] Which do occur, through Irving did not happen to strike one (U. S. Geological Survey Monog. V, p. 32). They are not thick or conspicuous so far as I know.

[9] Which may be briefly defined as clastic vein.

[10] See Fenner's discussion of the New Jersey Traps, Journ. of Geol. XV, No. 4, (1908) p. 299.

bluffs (*not* the Minnesota *then*). The 2,500 feet of beds between it and the Baltic conglomerate near Portage Lake contain not less than four well-marked red conglomerates, while the traps toward the base are good heavy beds (ophites) 100, and in the case of the Mabb ophite over 200, feet thick, with clinkery amygdaloid tops, very hard to distinguish from amygdaloid conglomerates, especially if at all disturbed. Marvine in Volume I of these reports numbered the conglomerates around Portage Lake. The four conglomerates just mentioned are his 8 to 5. For further details see especially Sections 5, 14 and 16 of Chapter V.

(2.) *Central (Mine) Group.* This group is as well exposed in the Central mine as anywhere else and in the diamond drill section thence south (q. v.). The Clark, Empire, Mandan, Manitou, Central, Phoenix, Cliff, Calumet and Hecla, Torch Lake, La Balle, Franklin Junior, Arcadian, Isle Royale Consolidated, and Winona sections (q. v.) all develop this series. The various exposures in Houghton village from the College of Mines to Hurontown creek beyond the Copper Range station, show the beds. This is a new name I have introduced, naming it after the Central mine, with the thought also in mind that it really covers physically the center and backbone of the Keweenaw Ranges. I placed the lower limit at the top of the Bohemia conglomerate, and the upper limit at the St. Mary's "epidote," a small genuine volcanic ashbed which often looks jaspery and occurs just above the Greenstones.

Thus limited this group is characterized by few and thin conglomerates,[13] but numerous, and at times very thick, lava flows of uniform composition, on the whole not far from that of the standard ophite.

On Black River the thickness of the group is possbly 25,000 feet, at Portage Lake (90 + 2835 + 3015—27) 5913 feet, out on the Point about 7,000 feet, on Isle Royale (6115—2045) 4070 feet.

Of Marvine's numbered conglomerates, 15 to 9 occur in the Central mine group.

The Allouez or Albany and Boston conglomerate just under the Greenstone is 15, and is not far above the Medora lode.

The Houghton is often a triple amygdaloid conglomerate and is No. 14. The so-called Montreal lode is near it.

The Calumet conglomerate is the lucky 13.

The Kearsarge conglomerate is a heavy conglomerate around Calumet and appears to cover Marvine's 12, 11 and 10, but seems to split back of Houghton.

The Wolverine sandstone is generally, but not always, a deep red sandstone and is No. 9. It is only a short distance below the Kearsarge lode, separated from it by a trap bed showing large porphyritic feldspars, and a long way above the Isle Royale lode. For details of distances between these beds reference must be made to the detailed sections and correlation tables.

The culmination of volcanic activity is in this group. The thickest individual flow is probably the Greenstone which in the Manitou section is 1130 feet thick, but for a continuous succession of flows with no important sediment the three thousand foot interval between Conglomerate 9 and the bottom seems to hold the record.

The general course of this group and its conglomerates is made easier to grasp by Figure 8. This is an outline of Plate VIII.

(3.) *Ashbed Group*. This group was named from the Ashbed mine, and old mine which has not been worked since 1900, whose property covers a strip from the Lake Shore to the center of Section 23, T. 58 N., R. 31 W. The mine itself was so named presumably from an intention to exploit one of the amygdaloid conglomerates known by the miners as the Ashbed (Marvine's No. 17). It includes Conglomerates 16 to 18, and is characterized by lavas which contain more soda than the regular ophites and which are relatively feldspathic and fine grained.

The feldspars in these lavas appear white or green on a green or reddish ground, and are often clotted together (glomeroporphyric). As we go toward the Porcupine mountains a genuine red felsite appears in a thin horizon between Winona and Rockland. I think it extends uninterruptedly to beyond the Black River section, and forms the main mass of the Porcupine mountains. This region seems to have been the center of its dispersal. Intrusive felsites are found in the Porcupines and between them and Lake Gogebic. The Tamarack shafts are sunk in this group. It is 2400 feet thick there, but on Isle Royale (2045—806) only 1239 feet

I am tempted to regard the Mesnard epidote, which is a volcanic ash. as a correlate to this felsite. At any rate, associated with it are some conspicuous porphyritic beds of darker color, which may represent the other beds of the Ashbed group. If one considers that this horizon can be fairly well followed throughout Michigan, even across Lake Superior to Isle Royale, one is justified in expecting it elsewhere, for instance, in the Temperance River group of Minnesota.

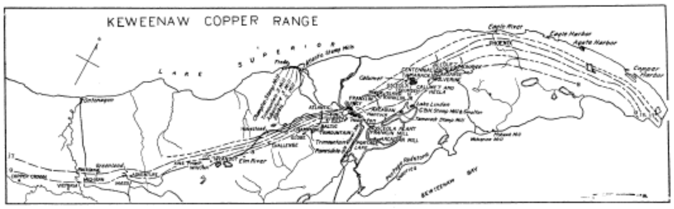

Figure 8. Outline Map of the Keweenaw Copper Range. After Mines and Minerals, 1906, p. 205.

(4.) *Eagle River Group*. This group is characterized by waning volcanic activity. It contains numerous sandstones and conglomerates, and on the whole they are more rounded in this group than in others. The individual lava flows are generally not thick nor coarse grained.

In this 2300 feet Marvine estimates 860 feet of sediment. Around Calumet 1700 feet may be assigned to it and on the Black River north of Bessemer 1417 feet.

Tamarack shaft No. 5 reaches downward to a point a little above the top of the Ashbed group, while shaft No. 2 starts at a point nearly down to the Kearsarge amydaloid giving a section from 3640 feet above the Calumet and Hecla to 1420 feet below (5060 feet), as illustrated by Figure 9. See also the cross-sections in Volume V, Part 1, and elsewhere given in this report. (Figs. 36 and 37.)

The conglomerates which occur around Copper Harbor were treated and mapped together by Douglass Houghton who considered the intervening Lake Shore Traps to be intrusive dikes. When were found to be continuous interbedded flows the conglomerate above the traps was called the Outer conglomerate, the one below, the Great conglomerate. Hubbard showed that there is at least one conglomerate separated from the Outer by trap above it and from the Great conglomerate by trap below. This he called the Middle conglomerate. But we do not know that these traps which break up the mass of conglomerate and represent the last phase of volcanic activity in the Lake Superior region are everywhere persistent,—in fact north of Calumet they almost disappear and they have not been found in the vicinity of Houghton. So there seems to be a real need for a name for the group as a whole and after consultation with a number of fellow workers "Copper Harbor conglomerates" seems to be best. When they are separated by the Lake Shore traps into two or three parts one can still apply the adjectives Great, Middle and Outer, and indeed need not always give them the full title. For "Great Copper Harbor conglomerate," or "Middle Copper Harbor conglomerate/' one may still say "Great conglomerate" or "Middle conglomerate" when the meaning is clear.

The disadvantage in thus grouping the conglomerates is. that Irving made the line between Upper and Lower Keweenaw at the highest and youngest known[14] igneous rocks, the top of the Lake Shore Traps. Thus the Outer Copper Harbor conglomerate is the base of the Upper Keweenawan.

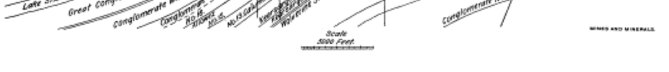

Figure 9. Outline cross section near Calumet. After diagram prepared for Mines and Minerals, 1906, p. 204.

(5.) *The Great Copper Harbor Conglomerate* is a coarse heavy conglomerate at base, with large generally well rounded pebbles of great variety, mainly Keweenawan. Its thickness, not allowing for initial dips, varies from 1800 to 2200 feet at Eagle River and Calumet to possibly 340 feet (?) on Black river, but apparently it is much thicker in the Porcupines.

The top of this group under the Lake Shore trap in the Porcupine mountains is a hardened red mud which is highly charged with epidote and calcite and occasionally with copper. Throughout the formation there are, above the base, alternating streaks of more or less coarse red sandstone and mud rock (red shale) and true conglomerate. Conglomerate is generally the most conspicuous.

(6.) *The Lake Shore traps* are a series of flows, none very thick, the total thickness varying from 1800 feet at the end of Keweenaw Point to 900 feet at Calumet and 400 feet on Black river. They are apparently absent around Portage Lake.[15] They represent the last volcanic outbreak in the Lake Superior region. The Lake Shore traps are melaphyres without any very distinguishing trait. The amygdules are generally rather coarse.

(7.) *In the Outer Copper harbor conglomerate* on Black river may be found pebbles representing all the Lower Keweenawan types including intrusives, amygdules and agates, and also Huronian iron bearing jaspilites and other rocks. A thickness of only 1000 feet is given for the Outer conglomerate on Keweenaw Point. Gordon makes the thickness 5000 feet on Black river, Irving 3000 feet in the Porcupines.

The upper quarter is largely sandstone, the lower quarter largely conglomerate. The Nonesuch lode is *really* in this formation just under the Nonesuch shale, being a rather striking conglomerate, the general body a coarse greenish sandstone or fine conglomerate in which are bright brick red pieces of red rock (gabbro aplite). The analysis of the Point Hough ton sandstone would probably fairly represent its composition.

The presence in these Copper Harbor Conglomerates of numerous pebbles which, if correctly identified, are of rocks intruded into the Keweenawan at some depth, and of agates, etc., formed in them tends to show that the earlier part of the series must have been considerably eroded, being either uplifted or forming from the very first a land formation exposed to erosion. As erosion continued the knobs of felsite, the harder quartzose red rocks, seem to have been worn down the material becoming finer with more of the dark basic lavas in the sediment.

(8.) *Nonesuch Shales*. The Nonesuch shales are quite uniform and persistent in thickness, appearance and distribution. Their thickness is 350400 feet on the Montreal, 500 feet at Black river, 600 feet in the Porcupines, and somewhat the same near Rockland. Thence north their occurrence is not so well known, but they appear to pass Portage Lake on the powder company's lands, Section 28, T. 55 N., R. 34 W.

The shales are black, fine grained, micaceous, sometimes greenish, and grade into greenish flags or grits and sandstones. Some of the sandstones have bands of iron ores which completely cover the cleavage faces. The black color is, therefore, due to iron and chlorite and not to organic matter as the analysis proves. It has no more iron than the red sandstones, but the iron is combined with alumina, magnesia and silica, into green minerals like those which occur in the altered conglomerates and amygdaloids. The Nonesuch must have been formed under such conditions that the iron oxides did not readily rust and oxidize. It preserves, beautifully, ripple marks and mud cracks, and seems also to contain traces of crawling animals or sea weed. (Pl. V.)

(9.) *Freda Sandstones*. Above the darker shales and grits of the Nonesuch, red beds appear again,—generally a red, impure sandstone, sometimes conglomeratic and sometimes red shale, in general much like the Outer and Great conglomerate, except that the conglomerate becomes less and less abundant. The higher beds were well exposed near the new stamp mills at Freda and all along the adjacent shore. A drilled well at Freda showed a thickness of not less than 900 feet. They can not be less than 1000 feet thick there though the dip is much flatter than the beds above, more like 10 degrees to 30 degrees from 4000 feet to 12,000. Irving estimated 12,000 feet of thickness in the Montreal section. I strongly suspect a repetition by faulting there, but even if this is so there can be hardly less than 4000 feet.

The relation of these sandstones to the Jacobsville sandstone, and the Apostle Islands sandstones, which all agree to be Cambrian, is a moot point. I believe that the Freda sandstone correlates with the beds of Clinton Point, which Irving grouped with the Cambrian. A full discussion of the grounds for and against the Cambrian age of the Keweenawan must needs be technical, but the writer is inclined to class the Keweenawan as Cambrian, and this much at least of the argument anyone can appreciate, that between the formation of the Freda sandstones and that of the Upper Cambrian sandstones, which are similar to them, nothing is positively known to have happened,—no igneous activity for instance.*

§ 8. SOURCE OF THE COPPER.

Much thought has been spent upon the question of the source and distribution of the copper. After Pumpelly's masterly work on the copper bearing lodes,[16] and the summaries given by Irving and Wadsworth especially, little needed to be added for years. Additional facts have been accumulated, however, and with the growing importance of the western deposits, there has appeared a tendency to apply the same principles that have been used in explaining them to these and other similar deposits of native copper and ascribe the copper to solutions rising through fissures from beneath, charging the formation with its precious content. This view has been especially represented by Smyth and Van Hise. Those connected with the Michigan Survey have never accepted this view but have believed that the copper belonged to the Keweenawan formation itself, and had been segregated therein by wandering waters, which have been generally thought of as working downward.

This whole report is an assemblage of facts bearing on this problem. A few points may be grouped here.

1. The dissemination of copper in small quantities throughout the formation. The average from several thousand feet of drilling at the dark-Montreal was 0.02 per cent. Hardly a single amygdaloid fails to carry less than .02 per cent copper, and when the copper content reaches .50 per cent it is nearly an ore.

2. The occurrence of native copper in similar formations of red rock associated with salt waters and lavas elsewhere,—notably the New Jersey Triassic, in the Bolivian Puca sandstone, in Nova Scotia, around Oberstein in the Nahe melaphyre region, and in Alaska.

3. The general absence of native copper outside the Keweenawan, in the Lake Superior region, but—

4. Native copper has been found in iron ores (generally thought to be formed by the action of downward working waters) in a few places.[17]

5. The water in the formation is of three kinds:

a. At and near the surface, soft and fresh with sodium in quantities more than sufficient to combine with the chlorine.

b. At some distance (generally 500 to 2,000 feet, before it attracts attention, unless especially sought), the chlorine is higher and the water is charged with common salt. The line between the two classes of waters is often quite sharp.

c. At great depths a strong solution of calcium chloride containing some copper.

6. The middle water (b) often contains more salt than it could possibly have were it a mixture of a and c.

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[11] Annual report for 1905.

[12] The arguments will be given later. Briefly, the strong group of Conglomerates 8 to 5 are not represented between a narrow felsitic band which almost surely represents the St. Louis conglomerate and Mount Houghton felsite horizon, and the dips of the Torch Lake and Douglass Houghton section are flat enough to swing these conglomerates into line. In that case the Isle Royale Consolidated section would show (721 + 1753) (2473) feet of this group at Houghton down to the Baltic conglomerate and including the Baltic lode, the base of the series not being reached. Unless there is repetition by faulting the workings of the Lake and North Lake and similar developments would also be in this group.

[13] 5.65% of 8,500 feet at the Arcadian, 6.65% of 6,247 feet on Isle Royale (400 to 500 feet of sediment).

[14] The one occurrence, reported by Irving, of a dike cutting the Upper Keweenawan near Lone Rock north of the Porcupines, proves not to be such.

[15] See Chapter V for discussion of relation to Middle conglomerate.

*See also U. S. Geol. Survey Monograph 52, pp. 413-419, and p. 379. In this Monograph doubt is thrown on the Cambrian age of the Apostle Islands sandstones, but my view as to their relation to the Freda is accepted.

7. The lines between the different kinds of waters are not regular, yet the lowest water probably always comes within two or three thousand feet.

8. The amygdaloids seem, other things being equal, to contain rather stronger (more saline) water than the conglomerates.

9. An unequally heated solution corresponding in composition to mine water (c) will precipitate copper on the same minerals, prehnite, datolite, etc., on which it occurs in the mines, as Fernekes has shown.

10. The traps contain combustible gases, as R. T. Chamberlin has shown.

11. Certain beds are abnormally high in copper for many miles.

12. Copper often replaces chlorite, and in the Calumet and Hecla pebbles chlorite replaces felsite, and the copper the chlorite.

13. Copper may even replace vein quartz,

14. Copper is formed generally after those minerals which are the products of alteration and contain lime, and before those secondary minerals which are the products of alteration and contain soda and potash.

15. Therefore at the time the copper formed the mine water might have lost lime but could not have lost sodium. The rock might have lost both.

16. The Calumet and Hecla lode averages less rich (very rich in spots) near the surface, attains its greatest richness at a certain depth, say about 2,000 feet, and then gradually decreases in richness.

17. The silver occurs more abundantly in the upper levels.

The conclusion to which these facts have forced me is that the copper was in the Keweenawan formation as a whole, before being introduced into the particular places where we find it, and that the deposits have gathered together[18] by migration of the particles known as ions in the chloride solution, just as in the formation of electrolytic copper in an electrolytic bath the copper goes toward the electro negative pole and the more electro positive or alkaline parts of the solution, and as in Fernekes' experiments, toward the (hotter parts of the solution. That the copper should actually be precipitated as a metal, however, depends upon a delicate adjustment of the composition of the solution in which the affinities of iron for oxygen may play an important part. For the copper to be precipitated the solution had to be kept neutral or alkaline and reducing in the part where the precipitation took place. And in the accumulation of copper into workable deposits not merely the electrolytic migration of the copper in the solution but the currents and circulation of the solution of the water in the rock have to be considered. In producing this solution and guiding its circulation, the following factors have to be considered:

(1.) The water originally contained in the lava.

(2.) That which early filled it whether it was buried on land or beneath seas, which may have included condensed volcanic vapors containing copper chloride as in Stromboli, or in the evaporation of desert pools.

(3.) The absorption of water in the hydration of the rocks.

(4.) The absorption of water in the cooling of the formation (water in cooling shrinks more than rock).

(5.) Faults in the formation facilitating the intermingling of solutions of different compositions.

(6.) Erosion of the formation and concentration of the copper contained either in pools on the land surface or in the water which found its way down into the rocks, while the deposition of the Keweenawan as a land formation was going on.

(7.) The ordinary circulation of the water entering at the higher parts and emerging in springs.

Now, all of these may have had some influence. Most of them *must* have had some. It may well be that the next great discovery of copper will be one of a new type in which some factor so far apparently unimportant becomes the dominant one.

As to the importance of these various factors, however, a few words may be said, though reference must be made to the detailed work. Absorption of water seems to me of first importance in the accumulation of copper, round and round circulation of less. To suppose that the wide spread calcium chloride waters are always volcanic is to suppose that the earth is everywhere sweating,— a sweat salty with calcium chloride. But to this theory there are serious objections. It must remain unsafe then to say to just what extent various sources participated in formation of the mine waters. We may, however, look back to a, time when the formation was filled with a water whose main acid was chlorine, but the base was not sodium. This is the practically important thing. Whether oceanic in origin or not these chloride waters are as universal as the oceanic when sufficient depth is attained, and though they vary in strength for the same depth, I have not yet been able to find signs that, other things being equal, there is more chlorine near certain fissures or in certain districts. The reverse of this, that there is sometimes less chlorine near fissures where the circulation has obviously been free, is true. This may be used as an argument against the introduction of the chlorine from without.*

In the accumulation of copper, and after soda may have replaced lime in the mine water, an early occurrence of salt water of the calcium chloride type does not appear especially favorable. In the upper levels, however, where the water is fresh and there has been a good deal of circulation, the copper may be all washed out.

The distribution of the copper in a lode may perhaps be likened to that of the matter on a slime table, bare at the center or top, heavy in spots and streaks in the middle, more uniformly but thinly scattered toward the lower and outward margin.

One thing is noteworthy in a number of cases—a tendency for the copper to accumulate under heavy impervious beds, extending perhaps in thin sheets up into the joints of the same,[19] but even more in stringers into the foot as described by Wadsworth. In such cases the heavy bed has evidently guided the circulation.

§ 9. GASES.

Combustible gas has been found in mine waters, notably at Silver Islet, but also at the Calumet and Hecla. It was natural to attribute it to decaying timbers but that explanation seems no longer necessary since R. T. Chamberlin has found that most igneous rocks yield about 1 or 2 times their volume of combustible gas.[20] Such gas or the hydrocarbons or carbides, nitrides, and silico-chlorides (found by Brun to be normal constituents of lavas) from which they might be derived[21] are powerful reducing agents that might throw out the copper.

Thus Pumpelly's explanation that ferrous salts precipitated the copper though both possible and plausible, is not absolutely necessary. It may be original carbon which produced the calcite which is the mineral most intimately associated with copper. One may readily find crystals of Iceland spar ($OaCO_3$) intergrown with native copper whose virgin luster is thus beautifully preserved. Some times the crystal form of calcite (the "dog-tooth"—or other shape) is plated with copper and the growth of calcite continued. Now carbon dioxide is absent from the lower mine watery though calcite is present in the rocks and a certain amount of carbon-dioxide gas may be abstracted from, them. It is easy then to suppose that a slow oxidation of hydrocarbons and carbides originally in the beds has furnished the carbonate, which formed slowly since it is in large crystals, and reduced the copper. We are then not compelled to look to the waters beneath the earth for the source of the copper.

§ 10. ALTERATIONS AND MINERALS PRODUCED THEREBY.

Pile up a series of heavy massive beds (traps) and open porous spongy ones (amygdaloids) like a layer cake, and then tilt the pile and there can be but one result,—a slump and sliding of the upper beds and a crushing of the open porous beds as shown in Figure 10, until by a process of shattering, "brecciation" and filling up and cementation of the porous beds with new minerals, they are made of nearly the same specific gravity as the rest and strong enough to stand the pressure. This is what has happened to the amygdaloids. Even the most casual visitor will be able to see in the mine dumps and at the stamp mills the soft white cleavable calcite, the white or colorless glassy hard quartz, the yellowish green epidote, and the darker bluer greens of the chlorite (delessite) group, and serpentine. Prehnite, white with a faint greenish tinge, is a common associate of copper. Laumontite, reddish and readily crumbling, is not so favorable a sign of copper. Datolite, almost like porcelain, often with beautiful flesh, and other tinges, is one of the last minerals formed. Datolite is polished to form articles of jewelry as are also chlorastrolite, thomsonite and agate. The concentric banding of the agates, which generally are large amygdules, is cut across in making jewelry, while the chlorastrolite and thomsonite amygdules are polished round.

In general, laumontite, epidote, quartz and prehnite tend to antedate the copper, calcite and analcite are about coeval, while datolite and orthoclase are often later, but there is a good deal of overlapping. Sulphates like barite and selenite are rare and late comers and like the analcite and silver seem rather confined to the upper levels. I am inclined to think too, that the interesting sulphides and arsenides, the lead colored chalcocite, the tin-white chloanthite, the pale reddish nickeliferous Mohawkite, and Keweenawite, are also relatively superficial.

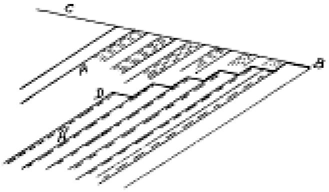

Figure 10. Illustrates the effect of slump in a series of traps and amygdaloids, the amygdaloids being originally vesicular porous beds as thick as the traps but crushed to a fraction of their original thickness, in which process the line CB takes the position BD and the bed A sinks to A'.

One of the striking factors in the development of stamp mill practice in the past 20 years is the introduction of the diagonal sorting tables of the Wilfley, Overstrom and Deister pattern, and a noticeable and beautiful feature in some of the mills is the production of bands of different colored minerals arranged on these tables according to specific gravity. Next to the copper red there may be a lead colored band of chalcocite present. The yellow-green band of epidote may next appear before we come

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[16] Volume I of these reports; Volume III of the Wisconsin reports.

[17] Report for 1903, p. 247.

[18] Been segregated.

*These waters are discussed in the Lake Superior Monograph 52 on p. 544. "In deep underground waters there is essentially the same condition of stagnancy, and therefore we suggest progressive accumulation of soluble chlorine salts." But in spite of the stagnancy Van Hise and Leith see "no adequate reason, for regarding these waters as fossil sea waters."

[19] Copper under the Lake Shore traps, under Nonesuch shales, under Greenstone, under Mabb ophite, etc.

[20] Including a sample from a deep core sent by us; "The Gases in Rocks," published by R. T. Chamberlin, pp. 20-24, 33, 34.

[21] Another possible reaction suggested in Chamberlin is: $6FeCl_2 + 3H_2O = 2Fe_2Cl + Fe_2O_3 + 3H_2$.

to the dull maroon iron rust colors of the red clays and ground up amygdaloid.

The amygdaloids sometimes have the original texture and round bubbles well preserved. Then again they are all brecciated, that is, broken up, the cementing material being calcite and epidote. Sometimes epidote and quartz replace the whole rock almost solidly. Again there is much chlorite. Where great sliding (actual motion) has taken place the rock is reduced to a greasy red clay called fluccan which the miners used to wrap in a ball around their candles for candlesticks. It is much more greasy feeling than the red sand or dust that blew into or washed into cracks in the lava and made what we call clasolites.

Figure 11. Illustrates gaping beds, or pile of cards when unequally bent.

§ 11. SHEAR ZONES AND SHOOTS.

If we bend a pile of paper and one part of the pile more than the other, we shall find between the parts thus bent a belt where the paper tends to gape apart (Fig. 11.) So in the uneven tilting and slumping of the formation we find changes of dip and strike and at times belts of traps which have been much fissured and shattered, in which secondary action and at times copper formation has gone on, by no means confined to any one amygdaloid, though normally, movement and readjustment would naturally follow the weaker beds, the sandstones and amygdaloids. But if there is a diagonal stress, neither at right angles nor parallel to these beds, the resultant disturbance will follow the weaker beds for some distance, then jump across through a heavier trap bed, shattering it on the way, when the diagonal component of the stress, not satisfied by yielding along the beds, becomes too great. Thus a shear zone will be produced (Fig. 11), which would in many have a tendency to gap open and leave places to be filled by breccia and new deposits.

It is certain that some of the stresses to which the Keweenawan rocks have been subjected, have had a diagonal direction. We have noted! a tendency of beds to be thrown to the right on the northeast which corresponds to the general eastward curve of the Point. As illustrated, the Quincy mine is not confined to one amygdaloid, and the Baltic lode appears to be in a shear zone,—the Lake perhaps also.

The Calumet and Hecla shoot is shown on Plate IX.

§ 12. SURFACE GEOLOGY AND DISTRIBUTION OF FLOAT COPPER.

After the close of the main up-tilting the copper range uplift may have continued in a lesser way since beds of the age of the Niagara Limestone are disturbed at Limestone mountain. There was later some depression, since about the time the hardwoods first became abundant a sandstone was formed in the Mesabi range[22] and the ocean may possibly have reached Michigan too, though no trace of such, sediments have yet been found. Probably before this time the surface was reduced to a comparative level, such as the plateau from the the Quincy to the Calumet, and some time since the Cambrian sandstones mantled the range (possibly when emerging from the Cretaceous sea), rivers seem to have established their course across the range, marking out valleys such as those now occupied by the Ontonagon river, Fire Steel, Flint Steel, and Portage Lake. These valleys may have been cut deeply in the era of elevation preceding the recent ice age, which is marked by the formation of caves such as the Osborn cave at Fiborn and by the deep valleys in the rock surfaces, now filled with drift, whose soles are at times below sea level. At the same time the minor tributaries in their erosion brought out the rock structure, generally leaving the harder traps in ridges. When the ice age came on, the earlier center of collection and distribution seems to have been northwest of Lake Superior. It is called the Keewatin center. Later the ice moved from the east, from a center in Labrador called the Laurentian center, and reaching Lake Superior moved out from it. (Fig. 49.) Around Portage Lake the ice actually moved to 10 degrees north of west. This direction of ice motion is beautifully marked near the Calumet, Arcadian, Quincy, and Isle Royale mines. One can see the stoss and lee sides of the motion, the grooves and trails left by harder knobs. The ice front, which was naturally perpetually oscillating, and the direction of ice motion and transportation, streaming away from the center of distribution and finishing at right angles to the front, also shifted. Hence copper may be found either side of its parent ledge, but that at the surface which is most likely to be found was probably left by the last ice motion. Around Calumet and Portage Lake the ice moved from the direction of Keweenaw Bay, and farmers plowing their fields near Portage canal reap a harvest of copper nuggets which may have come from, the Franklin and Quincy.

From somewhere about the Winona mine on the south, however, the motion was from the other side. Where the motion was from the east and southeast over the eastern sandstones the surface overburden, or drift, is more sandy. The material which was ground off the range itself by the ice is a much stiffer red clay with stones in it. Great quantities of material were washed out of the ice front by water from the melting ice and deposited in sheets known as sand and gravel plains, irregular mixed masses and high hills known as kames, and long narrow hogbacks, known as eskers. Along lines where the ice front lingered some time the deposits are extra heavy and are called moraines.

Keweenaw Point and the Porcupine mountains were relatively early laid bare and made cusps or reentrant angles in the ice front. At one stage of retreat Centennial heights, north of Calumet formed a reentrant

(Plate IX). Another hill of sand, Wheal Kate (1508 feet A. T.), towers south of the Mill Mine Junction and the village of South Range, and is easily recognized from the hills either side of Portage Lake. It is part of a heavy moraine which extends entirely around Keweenaw Bay and for miles south the drift is extra thick. Working through this coating which is often of light quicksand, makes explorations and mining difficult, and will retard mining development.

In front of the ice sheet the water was ponded and drained to the Mississippi. On the north side of the Porcupines the highest level of this water was 559 feet above Lake Superior. On the south side of the Porcupines it was higher, at least 34 feet above Lake Gogebic, or 720 above Lake Superior, or 1320 above tide. But around the Ontonagon Valley the beaches and benches at 565 feet above Lake Superior are much more strongly marked. The corresponding level rises as one goes out on the point, being at North Tamarack at least 640 feet above Lake Superior. Thence downward are beaches at numerous different levels formed at successively lower stages of the water. Down to 480 feet above Lake Superior (a strong beach, well-marked, where the electric road crosses it in climbing a hill near the Quincy mine), the beaches are referred to a Lake Duluth. Thence down to a little less than 100 feet above Lake Superior, the level of the strong terrace on which the College of Mines stands, the beaches are said to be of a Lake Algonquin,[23] which covered all the upper lakes. It was drained at different periods by various outlets, a part of the time by the newly reopened Chicago outlet.

Strong beaches below the Algonquin, 30 to 60 feet above the lake,[24] are referred to a Lake Nipissing which had an outlet down the Ottawa. Possibly the bluffs and terrace on which the Freda stamp mills were placed were formed at this time. The Ottawa outlet has been raised by tilting of the land and there is reason to believe that this is still going on so that the Michigan shore sinking as well as being cut back by Lake Superior. This is very evident along the lake shore in the Porcupine mountain region.

CHAPTER II. NOMENCLATURE AND CHEMICAL RELATIONS OF THE KEWEENAWAN ROCKS.

§ 1. HISTORICAL REVIEW OF NAMES APPLIED TO IGNEOUS ROCKS OF THE KEWEENAW SERIES.

I wish to express especially my obligation to a paper by A. N. Winehell, published by permission of the Director of the U. S. Geological Survey[1] which I understood would represent the usage of the U. S. Geological Survey in their Lake Superior Monograph. Wherever I differ it will generally be found to continue the previous usage of the State Survey, and in this (my final report probably) it seems well not to change without the best reasons. Winchell has in view especially microscopic petrography, and his study of usage goes back therefore only to the microscopic studies of Streng (1877). Since I have in mind more the convenience of mining engineers and geologists in the field, I will go back a little farther, to give more completely the use of the terms.

Douglass Houghton in 1841 used the terms *Trapp* and *range*, and distinguished the *amygdaloid* from the compact *trap* or *greenstone*, which he defined as the compact granular variety made up of feldspar and hornblende, though he expressly stated[2] that under this term, augitic and other rocks were included. As a matter of fact, hornblende is rare in the Keweenawan rocks, and the mineral associated with the feldspar in the greenstone is generally chlorite and augite.

W. A. Burt and B. Hubbard used Houghton's terms, but since in working for the U. S. Linear Survey, under the contract with Douglass Houghton, they had come upon the Mt. Houghton and Porcupine Mountain felsite and quartz porphyries they called them *red trap* and *trap porphyry*. In the Jackson report[3] in which the work of Burt, Hubbard, Jackson, and Foster and Whitney and others is mingled, the main felsitic rock of the Porcupine mountain is called *jasper* and the more coarsely porphyritic rocks southeast around Bergland *quartzose porphyry*. Foster and Whitney continue to refer to the *Trap range*. The greenstone was still considered to contain hornblende. Where columnar jointed and very fine grained it was called *basalt;* when it contained distinctly disseminated feldspar crystals *porphyry* (*porphyrite* as I should call it), and the crystalline and feldspathic varieties (Mt. Bohemia gabbro and gabbro ophite) are called *sienite*. They also mention *compact trap* (ashbed or porphyrite?), *trap breccia* (amygdaloid conglomerate?), *porphyritic trap* (like the Kearsarge foot?) and *epidote trap*. In regard to the use of the term *jasper*, the compact *quartz* or *jasper* is understood to pass into the quartz porphyry.

In Volume II they discuss the terms *trap* and *greenstone*—stating that most of the igneous rocks embraced in the term *greenstone* are labradorite or oligoclase and pyroxene with chlorite and thus the term *diabase* is applied to them by continental geologists. Melaphyre they mention for the first time as "a fine grained compound of labradorite and ilmenite and (probably) pyroxene. Basalt is divided into

> dolerite, crystalline aggregate of labradorite augite and ilmenite
> anamasite, a fine grained mixture of the same.

They recognized the presence of augite, though it was still put after the hornblende in importance and analyzed

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[22] Leith on the Mesabi Range, U. S. G. S., Monograph 43, p. 189.

[23] Leverett, Twelfth report Michigan Academy of Science, 1910, Fig. 7. Fig. 2 shows Lake Duluth.

[24] Leverett, loc. cit. Fig. 8.

the Greenstone (note the capital G) from the summit of the cliff at the Cliff mine as given below.

In 1850, Fr. C. L. Koch,[4] one of the founders of Saginaw, an educated German mining engineer, visited the district and recognized (p. 201) the dark mineral as augite, and determined the trap to contain augite and labradorite with some magnetite at times and believe it to be properly called *trap* or, if the magnetite was conspicuous, *dolerite* and the finer forms as *anametite*. No progress was made on Koch for fifteen years. Rivot, professor in the Ecole des Mines, at Paris,[5] used the same terms, *trap*, *amygdaloid*, *greenstone*, and was rather inclined to believe the traps to be metamorphic sediments. A. Winchell, 1860-61, did no detailed work on the *Trappose rocks*. Thus the nomenclature of the first generation of geologists and miners still in use, to which I cling so far as possible, may be said to be practically that of Douglass Houghton, Bela Hubbard and Foster and Whitney. Koch's work, published in German, was and is yet largely unknown.

The next work in considerable detail on the Keweenawan rocks was that of Thomas MacFarlane (who had just passed away) for the Canadian Survey in 1855.[6] He argued for the term melaphyre and also used *trap*. He speaks of the upper part of the melaphyre as being amygdaloid. He made numerous analyses. Some might object that his partial analyses were not accurate and that he overestimated the amount of chlorite. From the modern point of view his analyses are certainly incomplete, but they still have distinct value as showing what parts of the rock were attacked by acids, and have not been replaced. Even supposing that he overestimated the chlorite, the rocks which he calls *melaphyre* are exactly similar to those which around Oberstein and the region of the Nahe river in Germany have been called *melaphyre*.

Moreover, the use of the term melaphyre was continued. H. Credner, the eminent German geologist,[7] applied it to the rocks associated with the Calumet and Hecla conglomerate.

Pumpelly, with whom Credner worked, and Marvine,[8] adopted this term *melaphyre* (melaphyr) while they recognized that the chlorite is produced from hornblende or pyroxene. They distinguished the following varieties of melaphyre—an amygdaloid upper part, a central coarse grained part; fine grained with rubellan (altered olivine); and melaphyre porphyry. Marvine called the Greenstone with the big "G" *diorite*, appreciating its coarseness, but also confusing augite with hornblende? A. A. Julien,[9] described rocks from the iron country, and incidentally some Keweenawan dikes as Black *Dioryte aphanite* (355, 356). These same Keweenawan dikes, C. A. Wichmann[10] called diabase recognizing them as labradorite-augite rocks, but refusing to call them *dolerite* as Koch did, since he would limit that term to Tertiary rocks. He recognized the quartz diabase. His was the first application of the microscope to the examination of the rocks. Pumpelly in 1878 and 1880[11] continuing his work under the Wisconsin Survey, followed Rosenbusch's system and described many of the Eagle river rocks, and suggested that the term melaphyre should be replaced by the term diabase, classing the rocks as follows:

I. Granular plagioclase-augite rocks: with olivine (chrysolitic) diabase.

II. Porphyritic plagioclase-augite, with more or less unindividualized base: porphyritic diabase or, with olivine, melaphyre.

III. Granular plagioclase-diallage rocks,—gabbro.

He noted that of one great flow that I call *ophite*,— the *Greenstone*—some specimens are diabase, some (as Bed 108) near the base, melaphyre, others as (Beds 95 and 107) of the Eagle river section, gabbro.

The luster mottled rocks he described as *melaphyres*, but did not recognize the altered olivine in the Ashbed type of trap. This is not to be wondered at, for it is rarely fresh and practically *never* in superficial specimens, which were all he had. Pumpelly also made a distinction between *amygdaloid* and *pseudo-amygdaloid*, the latter being a variety of a rock resembling the amygdaloid in its speckled appearance, but the result is one of alteration, not of filling of original bubble cavities.

Irving also contributed to Volume III and found in addition to *melaphyre* and *diabase, quartz* and *granitic porphyry* and *felsitic porphyry*, which he was inclined to suspect were fragmental (brecciated felsites). The *gabbro* of the Wisconsin Survey included a gabbro proper, olivine gabbro, uralitic gabbro and orthoclase bearing gabbro, the diabase, an ordinary prevalent fine grained type with one or two coarse grained varieties, the Ashbed diabase type, a pseudamygdaloidal and true amygdaloidal phase.

Mosler in 1877[12] followed the usage of Pumpelly. In his Monograph V of the U. S. Survey,[13] Irving still following Rosenbusch's usage, makes the following classes (p. 37):

Coarse,—gabbro and diabase, olivine gabbro and olivine diabase, all free from orthoclase; orthoclase gabbro, hornblende gabbro, anorthite.

Fine,—diabase of the ordinary type, olivinitic diabase and melaphyre, Ashbed diabase and diabase porphyrite amygdaloids.

The noteworthy difference shown in the work of the decade 1877-1887 as compared with the work from 1866-1877 is the more frequent application of the term *diabase* instead of *melaphyre*. Rominger, in Volume V of the Michigan reports, written in 1884, though not published until 1895, drops the term *melaphyre* and speaks of *diabase* and *amygdaloid*, *quartz porphyry*, and *felsite*. Irving (loc. cit. p. 69) called nothing *melaphyre* unless there was residuary base (glass, calling them olivine gabbro, if coarse; *olivinitic diabase*, if fine.

Many rocks among the Ashbed diabases, that I would call olivinitic he does not so count, taking the altered porphyritic olivine to be altered augite perhaps. Herrick, Tight and Jones[14] followed Irving in referring to *diabases, diabase porphyrites* and *felsite porphyry*. Wadsworth in 1779[15] classified the basaltic rocks as follows:

	Feldspar		*Melaphyre*	*Tufa*
		Basalt		
Basalt	*Leucite*		*Diabase*	
		Dolerite	*Gabbro*	*Poroda*
	Nephelite		*Peridotite*	

In 1880 he gave a characteristically thorough review of the literature of the Copper districts. He uses the term *melaphyre* very frequently as a variety of basalt, uses the term *rhyolite* for the more siliceous, *trachyte* for the less siliceous felsites. He uses the term *melaphyre* almost as Macfarlane and Marvine did. Its derivation application is the same, though he defines it as an altered basalt, and uses it[16] somewhat under protest.

In 1887[17] he examined for the Minnesota Survey among others, many Keweenawan rocks. He mentions the term *ophite* as a variety of his basalts, which take the forms of gabbro, diabase, melaphyre or diorite, according to alteration. Characteristic of Wadsworth is the emphasis he laid upon secondary changes and the account which he took of them in his nomenclature. Many things, for instance micropegmatite, that I should consider primary, he (and Irving followed him), considered secondary. Yet I found as I worked with him for two or three years that we would agree in a great many cases in the application of names though disagree in our conclusions and definitions.

Yet I agree that melaphyre *may* be essentially altered basalt. His last formal work for the Michigan Survey was in 1893[18] where on page 90 he gives a classfication of rocks and on page 147 uses the term "clasolite" for a deposit of sediment in fissures. In 1897 he gave for the Lake Superior meeting of the American Institute of Mining Engineers a clear and interesting summary of his views on the "Origin and mode of occurrence of the Lake Superior Copper deposits," which was printed in their Transactions. (XXVII, 669.)

Bayley[19] in 1889-97 describes the Minnesota gabbros in some detail and also the Pigeon Point rocks. He found *non-feldspathic* varieties of *gabbro*.

Grant in 1893 and 1894, describes, for the Minnesota Survey, gabbro, diabase, granite and a marginal fades of gabbro. His *augite soda* granite is a red rock like Irving's augite syenite and granitells, or Bayley's soda augite granite.[20]

The work of Hubbard, Patton, and Lane began in Michigan in 1889-92. The first publication is in the 1892-3 report, though there the only Keweenawan rocks described under our own names were some diabases intrusive in the iron bearing rocks. We were fellow students under Rosenbusch and have since worked in close relation. We have tried to use terms as they are used by earlier writers, and we have also tried to apply them so far as possible to the same things. It does not bother the practical man who has only incidental use for a geological report if a rock be called a *melaphyre*, whether stress is laid upon the fact that it is pre-Tertiary or effusive, or is older and contains chlorite and is altered, so long as the hanging wall of his lode is in each case called a *melaphyre*. We therefore continue to use the term *melaphyre* as applied to many of the Keweenaw traps.[21]

I did, however, begin to use one term which is not new, nor as I supposed new in the sense in which I used it, but is new in the district, viz. the term *ophite*[21] as a short equivalent for luster mottled melaphyre, applying it also to rocks which had the same texture as melaphyre, but on too fine a scale to give the luster mottling appearance, and I prepared for Volume VI, a table showing my usage.

To others of the traps, I applied geographic names in the Isle Royale report (p. 170) such as

Tobin porphyrite=Rosenbusch's navites?

Huginnin porphyrite=(a kind of diabase porphyrite).

Minong Porphyrite=(akin to an augite andesite.)

I also prepared a field scheme.

Former Assistant State Geologist F. E. Wright, prepared for the Michigan College of Mines, a synopsis of Rosenbusch's classification of rocks which, though it was accompanied by no text, should nevertheless be considered, because so many of the mining men will have been by its use familiarized with its terms. The same .statement also applies to the names used in Kemp's Handbook of Rocks and "Ore Deposits of the United States."

I have remained fairly faithful to the usage in Volume VI, prepared by Hubbard and myself. The only important modification from Rosenbusch's system introduced by me[22] was the attempt to confine the the two chemically synonymous terms, *diabase* and *melaphyre*, respectively to dike and effusive rocks, a proposition which Rosenbusch, though granting its desirability on theoretical grounds, has not accepted[22] for reasons which may be practically sound. A good deal depends on whether it really is practicable to separate the intrusive rocks from, the coarser central parts of flows.

In 1903, appeared an important work[23] by a group of the leading American petrographers, which broke away entirely from previous names and made a host of new names, dependent on a complete chemical analysis, though there are methods given by which one may estimate from the chemical analysis the mineral composition of the rock, were it composed of certain standard minerals, and vice versa from the minerals actually present one may infer the probable place in the classification. The lines between the different subdivisions are arbitrarily drawn in the classifications and constituents like H_2O and CO_2 (which are liable to have been added in weathering, but are certainly in some rocks primary and are very significant genetically) are absolutely neglected; other constituents like ferrous and ferric iron, which are equally likely to be modified by weathering, are given much weight and some substances, which are hard for the chemist to determine accurately, are so important in the scheme that samples from the same rock mass apparently differing but little in composition will sometimes find pigeon-holes astonishingly far apart in the classification, without more difference in the analysis than may be due to analytical errors. Occasionally, therefore, there are rocks in the same group in the classification which have little or nothing in common other than the bare chemical factors by which they are assigned to that group. All of this simply shows that the classification is not perfect. Few things are. The authors, however, suggest a series of names for field use which are convenient and very much like those which it has been customary to use.

§ 2. WINCHELL'S CORRELATION.

Winchell, with a labor for which I am very grateful (as it corrected some slips in an unpublished table which I had prepared for my own use), has calculated the pigeon-hole and the position under the Quantitative Classification of all the rocks of which we have trustworthy analyses, and has prepared a table of these names, as well as of the older names.[24] It will, then, be well first to go over his table II, slightly modified as herewith given a "Correlation of Nomenclature of Keweenawan igneous rocks," making some comments and comparisons. One thing must be remarked which will account for a good deal of the variety. *The same dike of lava or the name lava flow* may differ very widely in different parts and especially at different distances from the margin, so that it will be absolutely different in texture and quite different in chemical composition in different parts. One great difficulty has been in applying a name to a rock mass and then trying to define the name afterwards. The characteristics of one part will not apply to all parts of the rock. It seems to me, therefore, permissible for the field geologist to apply to a whole lava flow a name which by strict definition will apply only to some large part of it. If we do not do that we shall be driven to using some arbitrary geographic or proper name or number. This indeed we do to some extent and speak of the "*Kearsarge foot*," Bed 87 of the Eagle river section, Arcadian flow 23, etc. But it seems to me it is a great help to comprehension and memory if we may also speak of the *Chippewa felsite*, the *Mabb ophite*, etc., without meaning thereby that the so-called *Chippewa felsite* may not frequently have more or less conspicuous phenocrysts and so be called more strictly a *feldspar* or *quartz porphyry*, or that the Mabb ophite may not be, at the very top, a glassy amygdaloid.

Going over the roll of names cited by Winchell we find that his use of the term *Granite* is agreed on by all. His use of the term *Quartz porphyry* is agreed to by all but A. N. Winchell, who would substitute rhyolite porphyry. The term rhyolite has not heretofore been applied to these rocks, though they are chemically and in origin equivalent to the Western rhyolites, and many of them show beautifully the bands marking the flow lines. On this point W. H. Hobbs said in 1900:[25] "The tendency of American petrographers seems to be to abandon entirely terms of the class *quartz porphyry* and to extend terms correlated with *rhyolite* to cover rocks which were previously included in both groups. This tendency seems to me to be an unfortunate one since it results in classing together rocks which are essentially unlike. There may be no important difference between a

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[1] Review of Nomenclature of Keweenawan Igneous Rocks, A. N. Winchell, Journal of Geology (Vol. XVI) 1908, No. 8, p. 765. See also U. S. G. S. Monograph 52, pp. 395-407.

[2] ”Memoir of Douglass Houghton, first State Geologist of Michigan" by Alvah Bradish, 1889, p. 177.

[3] Report on the Geological and Mineralogical Survey of the Mineral Lands of the U. S. in the State of Michigan. Senate Docs., 1st sess. 31st Congress, 1849-50, No. 5, Pt. III, pp. 371-935.

[4] Studien des Gött. Vereins Bergm. Freundé by Fr. C. L. Koch, Vol. VI. Parts 1 and 2 (1852).

[5] "Voyage au Lac Supérieur," by M. L. E. Rivot, 1885 Annales des Mines Vol. VII, p. 173 et seq.

[6] "Exploration géologique du Canada, Report des Operation's de 1863 à 1866," Appendice relatif aux Roches et Gites Cuprifères du Lac du Portage, Michigan, par Thos. Macfarlane, pp. 153-169. Translated in Vol. I Geological Survey of Michigan, Pt. II, pp. 9-12.

[7] Neues Jahrbuch für Min., 1869, p. 3.

[8] Geology of Michigan Vol. I, Pt. II, Copper Bearing Rocks, pp. 12-13.

[9] Microscopic Examination of Eleven Rocks from Ashland Co., Wis., Geology of Wisconsin Vol. III, pp. 224-238.

[10] Geology of Wisconsin Vol. III, pp. 621-627.

[11] Geology of Wisconsin Vol. III, Pt. II, pp. 27-49. Lithology of the Keweenawan System.

[12] Der Kupper Bergbau am Obern See in Nord Amerika von Chr. Mosler, Berlin, 1877.

[13] "The Copper bearing Rocks of Lake Superior" by Roland Duer Irving, U. S. G. S. Monograph V.

[14] Bull. of the Sci. Lab. of Denison University, Vol. II, Part 2 (Granville, 1887) pp. 120-142.

[15] Univ. Comp. Zool. Vol. V, p. 280.

[16] Proc. Boston Soc. N. H. Oct. 19, 1881, p. 259.

[17] Geological and Natural History Survey of Minnesota, Preliminary Description of the Peridotytes, Gabbros, Diabases and Andesytes of Minnesota, Bull. No. 2, M. E. Wadsworth.

[18] Report of the Board of Geological Survey.

[19] "Basic Massive Rocks of the Lake Superior Region" by W. S. Bayley, first three parts in Journal of Geology Vol. I, Nos. 5, 6, and 7, fourth part in Journal of Geology, Vol. II, No. 8, and Vol. III, No. 1.

[20] Numerous papers listed in Bull. U. S. G. S., No. 188.

[21] Bull. Geol. Soc. Am. Vol. 8 (1896), p. 406 Vol. 10 (1899) p. 15. See also U. S. G. S. Monog. 52, p. 398; and Science Vol. XXXII, p. 513.

[22] Bull. G. S. A., 1893, p. 273, Michigan Geol. Sur., Vol. VI, Pt. 1, p. 220. See Mikroskopische Physiographic, fourth edition, Vol. II, pp. 1160-1161.

[23] "The Quantitative Classification of Igneous Rocks" by Cross, Iddings, Pirrson and Washington. (Hereinafter referred to as the "Big Four") Chicago University Press.

particular *quartz porphyry* and a particular *rhyolite* but compare a drawer of hand specimens of the former with one of the latter and an argument is unnecessary to show that as a class they are essentially different. The *quartz porphyries* are as a class, devoid of vesicular and fluxion structures—they are in their method of occurrence hypabyssal—and they more generally show the effects of devitrification and weathering, etc." The authors of the Quantitative Classification, whom I shall hereafter refer to, for short, as the "Big Four," would keep the term *quartz porphyry* or *quartzophyre*. I should be tempted to confine the term *rhyolite* to porphyries in which lines of flow were a marked feature. *Felsite* becomes *rhyolite* for Winchell and Grant. Rosenbusch in his latest edition uses *quartzless porphyry* and *felsite* for the ground mass of a porphyry. It seems not inappropriate to continue to speak of porphyries in which the ground mass alone is conspicuous as *felsites*, and such is the usage of the Big Four for "non porphyritic, light colored, rocks."

Obsidian and *apobsidian* are terms applied by Winchell and Wright to certain Minnesota felsites. *Tuff* we all agree upon as a name for volcanic detritus. *Augite syenite* and *granitell* of Irving (the latter distinguished by having quartz), *granite* and *soda augite granite* of Bayley and A. N. Winchell and Grant and N. H. Winchell, are names applied to the *red rock* associated with the big gabbro intrusives. These rocks often occur in pebbles in the conglomerate. They correspond to my *augite syenite* or as I have called them, in accordance with my belief that they stand in the same relation to a gabbro as an ophite to a granite, *gabbro aplite*.[26] The typical thing is the dominance of red and plagioclase feldspar. They are fully described in Wright's paper.[27]

Quartz keratophyre and *granophyre* are terms in Rosenbusch's classification that have been widely applied to these rocks. Bayley found them applicable to some of his Pigeon Point *red rocks*, which he is inclined to believe are softened sandstones. The Big Four would dub them *syenites*. If there is really conspicuous quartz they would term them granite. Then such terms as *soda granite* and *soda augite granite* are fitting enough. Whether we need a term for both augite syenite and soda granite and whether *gabbro aplite* is a fitting one remains to be seen. The simple term *red rock* has also been used.

Felsite porphyry (Pumpelly) *felsitic porphyry*, (Irving), *felsite* (Hubbard and Lane), and *orthophyre*, (a technical Rosenbusch term, Lane), Winchell, N. H., Winchell, A. N., and Grant would call *trachyte*. The Big Four would class this rock as *felsite* or *feldspar porphyry* according as the feldspar phenocrysts were present or not. As a matter of fact, a good deal of the felsite almost free from phenocrysts will be found on careful examination to be feldspar porphyry or feldsparphyre. A *trachyte* for most writers is a modern glassy rock. These are not. The term *orthophyre* implies that the porphyritic feldspar is orthoclase, a thing that is is sometimes well to emphasize. Syenite or granophyre of Winchell and Grant, or *monzonite* of A. N. Winchell, is probably much the same as the *augite syenite* and granite and *granophyre* of other writers, because in this, the red rock group, the feldspars are always nearly balanced. *Augite diorite* and *melaphyre* of Pumpelly, *hornblende* and *orthoclase gabbro* of Irving, *hornblende gabbro* of Bayley, *gabbro aplite* (?) of Lane, *orthoclase gabbro* of A. N. Winchell, porphyritic gabbro of Winchell and Grant, which A. N. Winchell has bracketed together, form a rather heterogeneous group including, as near as I can judge, the very coarse centers of some flows, and perhaps some of the dike rocks that I should call *gabbro aplites*, but I have often noticed that next to them the rock in which they are injected is apparently more or less saturated with their magma. This may be the rock called *oligoclase gabbro*, and *orthoclase gabbro*. The Big Four would doubtless include them all in the term *gabbro*, but it seems hard to call the coarser center of a flow or a spot in the same a *gabbro* even though the augite crystals be two inches across, especially so long as the feldspars remain very fine. Such gabbros are different in appearance from, the typical plutonic gabbro, such as the great Bad River gabbro that begins north of Bessemer and perhaps extends to Minnesota. It is not really difficult to distinguish between them. If one character fails to help, another will. The coarse effusive is more open textured and the original pores are coated with chlorite or filled with some secondary mineral which does not replace any other mineral. Also, the feldspar and magnetite are often very muck finer grained than the augite. With the exception of these few effusives,[28] this group is plutonic and corresponds apparently to the porphyrite and Ashbed type of effusive of which these rocks are the plutonic equivalent. Wright puts them down on the Quantitative Classification as *Bohemial auvergnose*. I have not located the reference by A. N. Winchell to Irving's *orthoclase diabase*. Probably it is some variety of the *gabbro*, *Bohemial auvergnose*. The real plutonic gabbro has feldspar better crystallized than the effusive, owing, I presume, to the retention of mineralizers by pressure. The *quartz diabase* of Bayley, Lawson,[29] Lane, Winchell and Grant, and numerous other writers since Wadsworth and Wichmaun correctly described these rather small sized intrusives cutting the Huronian rocks is always intrusive, so far as the writer knows, and all agree in the nomenclature. What the writer calls *diabase* nearly every one would call *diabase*.[30] The *quartz diabase* is in no sense analogous to Diller's *quartz basalt*, where the quartz is in the form of corroded brotocrysts. *Enstalite* and *hypersthene diabase* is also, so far as I know, intrusive,— the Big Bay occurrence may be mainly hypersthene. No analyses have been made and it is hardly known in Michigan as a Keweenawan rock.

The advantage of narrowing the definition of a diabase so as to include (only the typically small intrusives, as suggested by me in Volume VI, is that we include a nearly homogeneous group which nearly all writers have agreed to call *diabase*. I defined it as a characteristically intrusive, not too coarse grained rock of the same chemical composition and essentially the same mineral composition as a melaphyre." The word "characteristically" is the ambiguous one. I think we might replace it now by saying that the rock is not glassy except very close to the margin, is not amygdaloidal and there are no cavities which show by concentric coatings of fibres of chlorite that they are the filled angular pores, originally filled only with gas or water, left in the contraction to crystallization. The last mineral formed is either augite or quartz or feldspar or perhaps analcite, etc. The feldspar is coarse when compared with the augite and, generally within less than four feet of the margin, is plainly visible in lath-shaped crystals a millimeter long. In distinction from the typical gabbro, the feldspar is sharper than the augite which is not so large, and there is generally a distinctly finer grain near the margin which is particularly dense in the diabases. On the other hand in the typical gabbros the grain may be coarser at the margin and even when it is finer, it may have solidified originally as glass, and the grains seem to have afterward devitrified into a rather characteristic fine grained aggregate. It must be remembered, however, that very many other writers do refer to *amygdaloidal diabases*, and call diabases many of the rocks which I call *melaphyres*. Others call them *basalts*.

The terms quartz diorite and diorite are used by writers from Wadsworth on, and so far as I know in the same sense, though of course the line between them and uralitic gabbro will, at times, be hard to draw. It must also be remembered that igneous contact metamorphism changes augite to hornblende.

Anorthosite is a term used by Lawson (as A. N. Winchell forgets to note) for Minnesota occurrences[31] and by various Canadian writers. It is a Latinization of Irving's name *anorthite rock*. A. N. Winchell would replace it by the term *plagioclasite* because the feldspar is not always anorthite. But the anorthite molecule is largely present. As it does not occur in Michigan except in pebbles, so far as known, we do not have to decide the controversy. *Gabbro*, *diabase*, and *melaphyre*, *olivine diabase* and *ophite* is the rubric at which there is most variation in names. In the first place it may be noted that there is (I think) no essential difference in chemical character implied by these names, though in the chemical classification some are II, 423, Adamellose; II, 534, Andose; II, 535, Beerbachose; II, 5445, Hessose (many); III, 534, Camptonose; III, 5445, Auvergnose (most). This latter in the writer's judgment covers most nearly the normal composition of the group and Winchell in fact assigns ten analyses to it. Silica 45-49 per cent, Al_2O_3 about 16 per cent, CaO about 10 per cent, iron oxide 10-13 per cent. These are the fundamental factors.

There is, however, a variation in the amount of lime and soda. The very same flow will show a variation in different parts in which, the calcium oxide will run from six to ten per cent; the part last consolidated runs higher in lime and seems to be thus nearer the eutectic. The potash, as will be readily seen in looking over the analyses, is always less than the soda and usually less than 3 per cent. The soda varies somewhat in inverse ratio to the lime. The various places in which these rocks are found in the chemical classification are partly due to this variation, but are also quite possibly due to inaccuracy of analysis. A little change by which the alumina gains at the expense of the magnesia, or titanium oxide at the expense of the silica, makes a great difference in the classification, and even a change, which may be secondary, in the condition of the iron from ferrous to ferric has an important influence. For this part of the classification the Quantitative Classification fails to be a useful guide in grouping together the really important factors.[32] It seems, therefore, that it would hardly be wise for me in a report in some sense final to change the names hereto fore used. I use the term *gabbro* for the deep-seated *intrusive* rocks in which the feldspar is usually as coarsely crystallized as the augite and both constituents are fairly coarse. The last interstices may be filled with quartz or rarely orthoclase or micropegmatite but are never empty. *Diabase* will be applied to the intrusive dikes and sills in which the feldspar is coarser than the corresponding feldspar in the effusives except in the doleritic type. The interstices are generally filled with, augite but the last interstices or so-called acid interstices, which I have-fully described,[33] may be filled with an intergrowth of quartz and feldspar known as *micropegmatite*. That the interstices were at one time filled with a hot solution which tended to react on the pre-existing minerals is quite plain. The doleritic type of the melaphyres differs from the diabases only in that the last interstices are more likely to be filled with concentric coatings of agate or chlorite and seem to have been very probably at one time gas-filled pores. There may have been some glass, but in the thicker part of the flows the chances are against the presence of residual glass and there are no signs of it.

Melaphyre is a term which I shall still apply, following the custom: from Macfarlane down, to the flows which make up the great bulk of the Keweenawan series. The upper part is generally amygdaloidal, with gas; bubbles filled by secondary minerals. There was, originally undoubtedly more or less glass, but this is now largely decomposed. Bubbles may occur anywhere in the flow and the exact width which one shall in different give the amygdaloidal portion is a very uncertain factor. It is not usually over five feet. When greater thicknesses are given it will often be found that the whole of one small flow has been counted as part of the amygdaloid. The upper part of the flow being called *amygdaloid*, the central part will (following the miner's usage) be called *trap*. In this more compact and massive part the original characteristics of the flow are often more distinct than in the upper part, where secondary decomposition has often gone on to a very considerable extent.

The division of the melaphyres into groups is made largely upon the basis of the appearance of the trap. In the first place, there may be large crystals of feldspar which seem to indicate that the hot lava from which the melaphyre came had started to crystallize under conditions of very slow crystallization and very possibly before eruption, so that the crystals are intra-telluric. Such rocks Rosenbusch would call (if the feldspar is labradorite as is often the case) *labradorite porphyrite* and Kemp and Pirsson would call them *basalt porphyry*, and in some cases, perhaps, *dolerite porphyry*. Streng called them *melaphyr porphyr*. The Kearsarge foot is one of the most characteristic of these labradorite porphyrites (see Pl. 7, core from; Mandan drill hole 18 at 90 feet), but similar rocks are also found abundantly toward the base of the series, both in the Bare Hill district on Keweenaw Point and also on the Gogebic Range where they are found just north of Bessemer and may be traced west into Wisconsin and east past the south end of Lake Gogebic. They may be found also in the Porcupine mountains.

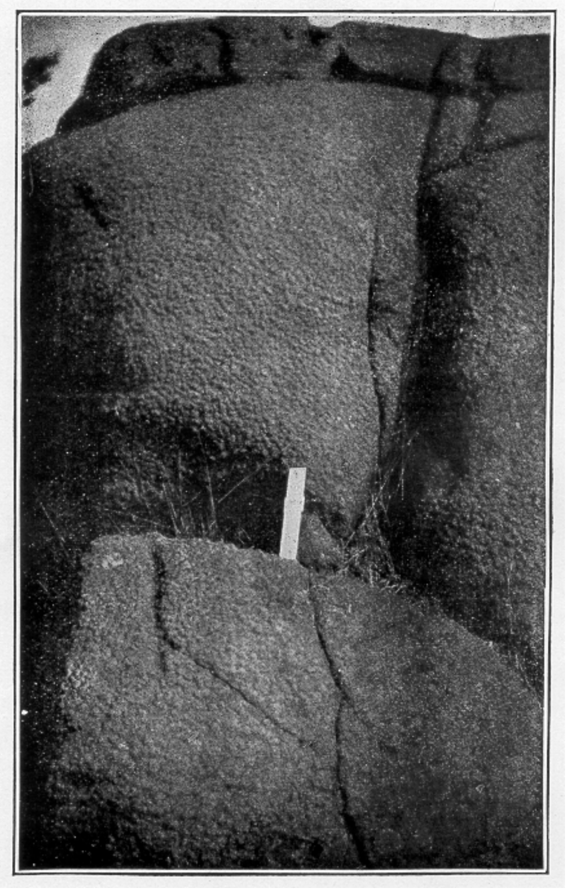

Plate II. Ophitic texture developing and pock marked appearance at the crest of the bluff of the Old Delaware mine, in the greenstone not far from the line of Manitou cross-section (Fig. 29) being back of the Old Delaware mine. Taken by W. J. Penhallegon, August, 1907. The white object is a slide rule six inches long and one inch wide and the exposure is about 100 feet from the base of the greenstone. Reproduced from Bull. Geol. Soc. Am., Vol. 18, 1906, Plate 71. See also Report for 1908.

There is another kind of porphyritic texture which occurs; especially toward the top of many of the flows. There are in this little crystals of feldspar, generally not more than one or two millimeters long, whereas the kind of which we have just been speaking are several millimeters in length and sometimes several centimeters, even an inch, in length. These crystals are frequently aggregated or one might almost say clotted like curdled milk. I have called this texture *glomeroporphyritic*.[34] It may be seen in studying a series of drill cores from the same flow (cf. Plate VII), Ss. 15295 and 15384) that from a distinct glomeroporphyritic texture at the top the rock may pass into an even grained texture at the middle or there may be at the middle a tendency to mottling due to the occurrence not of patches of augite but of patches of feldspar which have grown together. The texture I have called the glomeroporphyritic seems to be associated with an extra amount of soda. I do not think it is due to an intra-telluric stage of crystallization, that is to say, that these crystals started to form deep within the earth and their formation was interrupted by the volcanic outburst, but rather that the presence of so much soda tended to promote their crystallization in the shape of andesite feldspar before the eutectic in the final cooling, and before the lava came entirely to rest, perhaps, at any rate at an early stage of crystallization. It is thus a chemically significant texture. It may be found in various parts of the series, but it is especially characteristic of the Ashbed group above the Greenstone. This group I called in Volume VI the *Tobin porphyrites*. They are very close to Rosenbusch's *Navite family*. (See Pl. VII, Ss. 15295 and 15384.)

The final goal toward which these lavas seem to have tended in crystallizing, that is the most fusible and the last crystallising residue, is at the same time a most common independent type. Apparently, at an early stage there was a tendency for olivine to form, but at a later stage (probably at a lower temperature when augite could form) augite has taken the place of the olivine which has been reduced to corroded remnants and has been crowded ahead of the patches of augite. The feldspar is a labradorite and lime soda feldspar of a composition near Ab_2 An_3 which seems not to have crystallized as soon as the temperature fell to the point where it might have done so, as it does not become as coarse in proportion in the center as the augite. Still it precedes the augite and magnetite. The last thing to crystallize seems to have been the augite and the composition of the rock as a whole is not far from that of augite, nor is it far from that of Bunsens normal basaltic magma. (Table IV, and Fig. 12.) The result is that relatively small feldspars lie in a ground mass which is a cement or matrix of augite. In the coarser part of the flow the augite is so coarse that very many feldspar crystals are imbedded in one augite crystal. Toward the margin the augite is finer, so fine that a granular aggregate of several grains of augite may make up the interstices between the feldspar (which mainly occurs when there is a sort of transition to the glomeroporphyritic type at the top of the flow when the center is typically ophitic.) This is the structure which I have called *ophitic* and I have called the melaphyres which show this structure *ophite*. Winchell[35] is inclined to object to this. The question is discussed in the next chapter. The rocks are precisely those described by Pumpelly and Marvine who noticed the flashing due to the augite cleavages when the texture is sufficiently coarse and called them *luster mottled melaphyres*.

Finally, never as an independent rock, so far as I know, there are spots or streaks or sometimes long bands in the larger flows of melaphyre where the feldspar is much coarser, in fact all the crystallization is much coarser. The probabilities are that these occur where the mineralizers of the original magma were concentrated. They might be called *rudimentary pegmatites*. The feldspar is in all cases much coarser and sharply crystallized. The augite is also not infrequently distinctly crystallized, although its growth is more or less interfered with by the feldspar. Other crystals, such as magnetite, hematite and ilmenite also appear. The interstices last formed are commonly filled by chlorite in concentric coatings, as though it had filled cavities and it is these places that I have called *doleritic spots, doleritic melaphyre*, etc. Sometimes certain whole flows have an exceptionally strong tendency to this type of texture. The doleritic streaks appear in numerous places. In all such cases the feldspar, owing to coarser crystallization, is more conspicuous; whether there is really more feldspathic material in the rock I am by no means sure. I used the term *dolerite* because as generally used it implied coarse feldspar. If the term *dolerite* is to replace *melaphyre* or *diabase* as some have suggested, it may be better to call these *pegmatitic melaphyres*.

The above will, perhaps, give one some idea of the way in which names are used in this book. It is a common fault of the young student in reading older reports, such as those of Douglass Houghton or Hubbard to consider that they did poor geological work because they do not use the terms in the sense in which he has been accustomed to use them. It is unfortunate, but it seems unavoidable that with the growth of our knowledge the concepts which we imply by different words must somewhat vary and so it is always well to be careful in reading an author that one knows in what sense he uses terms. In the earlier geological reports it was very common to give at the end a little glossary or dictionary. The abundance of excellent encyclopedias and dictionaries have made this apparently unnecessary in geology, but just at present in petrography we are in the transition stage and are obliged to revert to the original usage.

§ 3. THE NOMENCLATURE OF THE SEDIMENTARY ROCKS.

The sedimentary rocks bear a strong resemblance to the rocks of the Permian and Triassic periods to which they were originally referred. They are prevailingly conglomerates and sandstones. The sandstones even include a great variety of grains of different sizes which are by no means wholly quartz. The sandstones are really fine grained conglomerates. There are other rocks of still finer grain,—red muds and shales which occur as streaks in the conglomerates. Sometimes these contain considerable white mica. This is of importance because J. Barrell has recently pointed out the the climatic significance of white mica in rocks of this nature.[36]

These red shales often contain ripple marks and mud cracks. I have not seen anything that I can call with certainty rain prints. There are here and there other curious markings like tracks such as those figured on Plate V. The Nonesuch formation is characteristically dark gray or black instead of red. This color is not caused by carbonaceous matter but by chlorite or iron ore. In fact, certain pieces of these rocks are as shiny with specular hematite as some of the black sands which one can now pick up along the shores of Lake Superior. This kind of black shale, therefore, which may be considered a characteristic rock of the Nonesuch formation, is not to be likened to the Devonian black shales or those of the Animikie beneath. In the region around Thunder Bay dolomites and dolomitic marls have been reported from the Keweenawan, but with these I am not familiar and A. W. G. Wilson tells me that their Keweenawan age is not certain.

In the conglomerates three or four distinct types can be recognized. In the first place there is the ordinary conglomerate with well rounded pebbles and a sandy matrix. In the Great conglomerate the size of the pebbles is somtimes very great and they are not assorted, yet the matrix is not clayey and on the whole they resemble much more the conglomerate found in gulches or *arroyas* in the west or a beach exposed to heavy storms than till. From these coarse conglomerates there is every gradation down to the finest and there are fine streaks of conglomerate in the sandstone and of sandstone in the conglomerate. Usually these conglomerates contain very little material except that supposed to be derived from, the Keweenawan formation. The porphyries are conspicuous among the

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[24] Journal of Geology, Nov.-Dec. 1908, Vol. XVI, No. 8. Monog. 52, p. 400.

[25] Journal of Geology VIII, No. 1, p. 6.

[26] Report for 1903, p. 236: Vol. VI, Part II, pp. 72-3; Report for 1904, p. 153.

[27] Report for 1908, pp. 361-393.

[28] Irving classes the Eagle River bed 94 as an *orthoclase gabbro*. But this is part of the big "Greenstone flow toward the top." I seriously doubt the presence of primary orthoclase.

[29] Minnesota Geological Survey, Bull. No. 8, 1893; Canada Survey, T. CC. 1886, 3F 1890; Canadian Inst: Proc. 5, 1886, p. 177-185; Am. Geologist Vol. I, 1886; pp. 199-211; Am. Geol. Vol. VII, pp. 153-164.

[30] Koch loc. cit. and Rominger Mich, Geol. Survey, IV, p. 145 use the term dolerite and so would Pirsson. If a felsite is to be called *rhyolite*, why not a diabase a *dolerite?*

[31] Minnesota Survey Bull. No. 8, 1893, pp. 1-23.

[32] See "Natural History of Igneous Rocks" by A. Harker, MacMillan & Co. Also his review of the Quantitative Classification, Geol. Mag. 1903, p. 178.

[33] Vol. VI, Pt. I, p. 235.

[34] Vol. VI, Pt. I, p. 167.

[35] Bull., Geol. Soc. Am., Vol. 20, p. 661. U. S. G. S. Monog. 52, p. 398.

pebbles. Yet where the Keweenawan formation approaches the old land masses, for instance, north of the Gogebic Range, pebbles of jaspilite from the iron ores and granite are common. So, too, the conglomerates at Mamainse contain a very large number of "Laurentian granites" and green "Huronian" pebbles which may be referred to the older rocks which lie a short distance further inland.

A second type of conglomerate, of which the Calumet and Hecla conglomerate is the most notable example, is composed almost exclusively of pebbles, and these of such extremely angular type that the rock has often been called a *felsite breccia*. Credner suggested[37] that this "bed of felsite breccia represented the upper end—the cap—of a felsite porphyry injection which had penetrated beneath the beds of the melaphyre amygdaloid following the same surface of separation, had consolidated on its way in part and then had been shattered by the fluid rock pressing behind and enclosed by the same." He expected that further opening of the Calumet and Hecla mine would show a transition of the breccia into a massive felsite porphyry and that perhaps the point would be found where it would appear as a dike crossing the bedded rock. This expectation has not been realized for the conglomerate as it is followed passes into other types of more common sedimentary conglomerates. If, however, he had left out the word "enclosed" and supposed that it were derived from the shattering of a superficial projection like the spine of Mt. Pelee, which, of course, had not come into existence at the time he wrote, there would have been something to be said in favor of his view, for beneath the Calumet and Hecla conglomerate to the southeast on the property of the Torch Lake Company a quartz porphyry has been found which seems to be truly intrusive and there are also felsites and this quartz porphyry appears to be the source of very many of the pebbles of the Calumet and Hecla conglomerate, although it is not uncommon to find pebbles of other types and more rounded forms belonging to more basic and softer beds. It seems on the whole best to explain these breccias by the well-known tendency of felsites to break up into angular blocks. Anyone who has attempted to trim out a good sized specimen, knows how difficult it is to get one of any size owing to the tendency to break up into angular pieces. If we suppose that the conglomerate is due largely to weathering and has not been transported very far this will account for the angularity of the breccia and this is what seems indeed, to be the case, for within two miles of the Calumet mine proper, the conglomerate has changed its looks entirely and passed into the next type which we shall consider,—the amygdaloid conglomerate. This transition was also found, I am informed, in part of the workings of the Tamarack Junior.

The third type of conglomerate is that which has been sometimes called *Ashbed* and which was called by my predecessor, Dr. Hubbard, *amygdaloid conglomerate*. On the whole for popular use the latter seems to be a satisfactory name because it gives at once its characteristic feature. It is a bed of conglomerate in which the pebbles are amygdaloidal. (See Pl. II B and Sp. 20485 of Pl. VII.) The matrix is generally a red, fine grained material which may be to some extent decomposed ash and to some extent decomposed melaphyre. In some places the fragments of amygdaloid appear to be derived by erosion from the top of an amygdaloid bed, but in many cases,—in fact I think most cases, they appear to be rather scoriaceous—the irregular, rough, open clinkery blocks of the upper part of a bed of lava of the aa type. In many cases, indeed, these pass down into an underlying bed so gradually, and the red matrix which cements the conglomerate proper may extend into cracks into the underlying lava so far that if one is studying drill hole samples only it is impossible to tell where the amygdaloid conglomerate ends and the lava underneath begins. For this reason I called them in Volume VI of my report *scoriaceous conglomerate* and the name tuff is not unfit, but as they occur so often in connection with the amygdaloids and as a given lode may in one place be an amygdaloid and elsewhere assume the appearance of amygdaloid conglomerate there are some advantages of continuity in names in using the term *amygdaloid conglomerate* which I shall therefore retain. This is especially true because some of the earlier writers seem to have lumped together the amygdaloids and amygdaloid conglomerates and the gradual transition from one to the other is the reason why many were inclined to think that the amygdaloid itself might be some sort of metamorphosed sediment.

In a few cases I have seen beds in which most ,of the bed or a good part of it was this fine red shale which may have been originally red mud but was mixed with an amygdaloid of a peculiar type extremely full of bubbles; so much so that it seemed derived from a pumice, fragments of which can easily be imagined to have floated along with the stream and settled, becoming thus scattered through, the red bed of fine material. In the Victoria mine crosscut there was a fine opportunity to study such conglomerate. I have felt the need of a somewhat different term than either of the terms previously used, and so I have used the term *pumiceous conglomerate*, really a highly amygdaloidal conglomerate with a great deal of cement. It must be of course, understood that as with all sedimentary beds these different beds are very likely to pass into each other and to show every gradation. At the same time a peculiar lithological character may be characteristic of one bed for a considerable distance.

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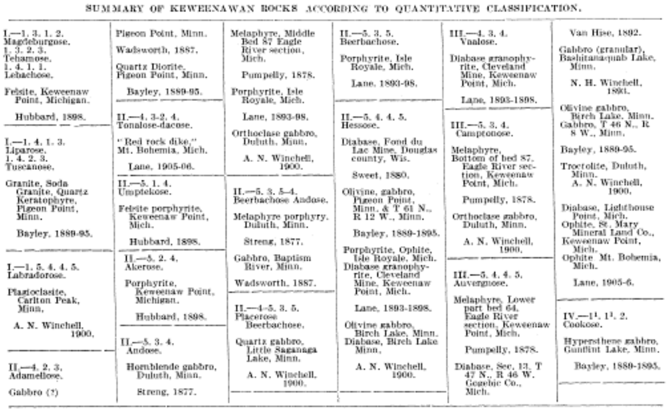
[36] Journal of Geology, 1908, p. 268.

[37] N. Jahrbuch f. Min. 1869.



SUMMARY OF KEWEENAWAN ROCKS ACCORDING TO QUANTITATIVE CLASSIFICATION.

I.—1. 3. 1. 2.
Magdeburgose.
1. 3. 2. 3.
Tehamose.
1. 4. 1. 1.
Lebachose.

Felsite, Keweenaw Point, Michigan.

Hubbard, 1898.

I.—1. 4. 1. 3.
Liparose.
1. 4. 2. 3.
Tuscanose.

Granite, Soda Granite, Quartz Keratophyre, Pigeon Point, Minn.

Bayley, 1889-95.

I.—1. 5. 4. 4. 5.
Labradorose.

Plagioclasite, Carlton Peak, Minn.

A. N. Winchell, 1900.

II.—4. 2. 3.
Adamellose.

Gabbro (?)

Pigeon Point, Minn.

Wadsworth, 1887.

Quartz Diorite, Pigeon Point, Minn.

Bayley, 1889-95.

II.—4. 3-2. 4.
Tonalose-dacose.

"Red rock dike," Mt. Bohemia, Mich.

Lane, 1905-06.

II.—5. 1. 4.
Umptekose.

Felsite porphyrite, Keweenaw Point, Mich.

Hubbard, 1898.

II.—5. 2. 4.
Akerose.

Porphyrite, Keweenaw Point, Michigan.

Hubbard, 1898.

II.—5. 3. 4.
Andose.

Hornblende gabbro, Duluth, Minn.

Streng, 1877.

Melaphyre, Middle Bed 87 Eagle River section, Mich.

Pumpelly, 1878.

Porphyrite, Isle Royale, Mich.

Lane, 1893-98.

Orthoclase gabbro, Duluth, Minn.

A. N. Winchell, 1900.

II.—5. 3. 5-4.
Beerbachose Andose.

Melaphyre porphyry. Duluth, Minn.

Streng, 1877.

Gabbro, Baptism River, Minn.

Wadsworth, 1887.

II.—4-5. 3. 5.
Placerose Beerbachose.

Quartz gabbro, Little Saganaga Lake, Minn.

A. N. Winchell, 1900.

II.—5. 3. 5.
Beerbachose.

Porphyrite, Isle Royale, Mich.

Lane, 1893-98.

II.—5. 4. 4. 5.
Hessose.

Diabase, Fond du Lac Mine, Douglas county, Wis.

Sweet, 1880.

Olivine, gabbro, Pigeon Point, Minn. & T 61 N., R 12 W., Minn.

Bayley, 1889-1895.

Porphyrite, Ophite, Isle Royale, Mich.
Diabase granophyrite, Cleveland Mine, Keweenaw Point, Mich.

Lane, 1893-1898.

Olivine gabbro, Birch Lake, Minn.
Diabase, Birch Lake Minn.

A. N. Winchell, 1900.

III.—4. 3. 4.
Vaalose.

Diabase granophyrite, Cleveland Mine, Keweenaw Point, Mich.

Lane, 1893-1898.

III.—5. 3. 4.
Camptonose.

Melaphyre, Bottom of bed 87. Eagle River section, Keweenaw Point, Mich.

Pumpelly, 1878.

Orthoclase gabbro, Duluth, Minn.

A. N. Winchell, 1900.

III.—5. 4. 4. 5.
Auvergnose.

Melaphyre, Lower part bed 64. Eagle River section, Keweenaw Point, Mich.

Pumpelly, 1878.

Diabase, Sec. 13. T 47 N., R 46 W. Gogebic Co., Mich.

Van Hise, 1892.

Gabbro (granular), Bashitanaqua Lake, Minn.

N. H. Winchell, 1893.

Olivine gabbro, Birch Lake, Minn.
Gabbro, T 46 N., R 8 W., Minn.

Bayley, 1889-95.

Troctolite, Duluth, Minn.
A. N. Winchell, 1900.

Diabase, Lighthouse Point, Mich.
Ophite, St. Mary Mineral Land Co., Keweenaw Point, Mich.
Ophite Mt. Bohemia, Mich.

Lane, 1905-6.

IV.—1^1. 1^1. 2.
Cookose.

Hypersthene gabbro, Gunflint Lake, Minn.

Bayley, 1889-1895.

§ 4. METHODS OF STUDYING CHEMICAL RELATIONS.

(1.) *The Quantitative Classification*. As we have above mentioned, some years ago there was prepared by a group of leading American students of rocks a system of classification dependent solely upon chemical composition. As A. N. Winchell[38] has recently determined according to this classification the position of all the Keweenawan rocks of which chemical analyses have been made, it will not be necessary for me to repeat his work. I have, however, summarized his table, and since many who read this report will not have the definitions of the different terms at hand we repeat them from the original publication in so far as it is necessary to make clear the relations of the different Keweenawan rocks.

CORRELATION OF NOMENCLATURE OF KEWEENAWAN IGNEOUS ROCKS WITH QUANTITATIVE CLASSIFICATION. AFTER A. N. WINCHELL.

All rocks are in Subclass 1 for which corundum and zircon < 1-7 of the rock.

CLASS I. "Persalane." Quartz and feldspar > 7-8 of rock.
Order 3. Quartz > 3-5 of feldspars but < 5-3.
Rang 1. "Peralkalic," alkalis > 7 CaO.
Subrang 2. "Dopotassic." 7 > $K_2O : Na_2O$ > 5 : 3.
"*Magdeburgose*" = felsite J. Hubbard, p. 28.
Rang 2. "Domalkalic," alkalis < 7 CaO but > 1.6 CaO.
Subrang 3, Sodipotassic 5 : 3 > $K_2O : Na_2O$ > 3 : 5.
"*Tehamose*" = Mt. Houghton felsite 17193 A, Hubbard, p. 42, silicified.

Order 4. "Britannare," quartz not so high, 3 : 5 > Quartz : Feldspar > 1 : 7.
Rang 1. "Peralkalic," "Liparase." $K_2O + Na_2O$ > 7 CaO.
Subrang 1. "Perpotassic" K_2O > 7 Na_2O "*Lebachose,*" felsite No. 16951.
Subrang 3. Sodipotassic. K_2O between 1.6 and 0.6 Na_2O.
Liparose Pigeon Point soda granites and keratophyres of Bayley.
Cf. Mt. Bohemia red rock and gabbroaplite.
Same Subrang but Rang 2 (domalkalic-alkalis) between 7 and 1.6 CaO.
"Toscanose" another of Bayley's keratophyres.

Order 5. "Canadare." 7 quartz < feldspar.
Rang 4. Docalcic, "Labradorase." CaO between 1.6 and 7 alkalis.
Subrang 3. Presodic, *Labradorose*, K_2O < 0.6 Na_2O, Winchell's Plagioclasite or Lawson's Anorthosite.

CLASS II. Dosalane and Dosalone quartz and feldspar > $\frac{7}{8}$ of rock.

Order 4. "Austrare" quartz between 3-5 and 1-7 of feldspar.
Rang 2. Domalkalic, Dacase alkalis between 7 and 5-3 of CaO.
Subrang 3. Sodipotassic *Adamellose*, Pigeon Point red rock. Bull. 109, U. S. G. S., p. 56.
A quartz diorite produced as a contact effect of a gabbro intrusion?
Same but Rang 3 or 2, Subrang 4 dosodic. Mt. Bohemia *Tonalose Dacose* of Wright, a red rock also associated with gabbro. ("Wet eutectic" ?).

Order 5. "Germanare." *All subrang 4 or* 5 dosodic Na_2O > 5 : 3 K_2O or persodic > 7 K_2O.
Rang 1. Peralkalic Umptekase and Umptekose, Felsite Porphyrite G Keweenaw Point, Hubbard, p. 26, 17039, 17007.
Rang 2. Domalkalic Monzonase and Akerose Porphyrite, Hubbard p. 25, Bed E, diabase porphyrite, Irving, pretty near Ashbed type.
Rang 3. Alkalicalcic, alkalis between 1.6 and 0.6 of CaO Andase and Andose, Isle Royale, p. 215, Nos. 15515 and 15519, Lane; and the Duluth hornblende gabbro, Streng; and Winchell; Eagle River 87 Ashbed type.
Subrang 5 to 4 Dosodic to persodic, andose or beerbachose Duluth melaphyre—porphyrite of Streng, N. J., 1877, pp. 48—117 and Baptism River Gabbro, Minn. Bull. 2, pp. 75-79.
On the line between Order 4 and 5, placerose—beerbachose, rang 3, subrang 5. Quartz just about 1-7 of feldspar, alkali calcic persodic. Quartz gabbro of Little Saganaga Lake, Minn. A. N. Winchell, Am. Jour. Sci., XXVI, 1900, p. 374.
Order 5, rang 3 subrang 5 beerbachose Isle Royale porphyrite (Ashbed or melaphyre porphyrite) 15537, same bed as the "Hessose" 15533.
Rang 4. Docalcic Hessase and Hessose.
Subrang 3 Presodic, Na_2O > 5-3 K_2O.
Diabase Sweet, Wis. III, p. 350. Douglas Co., Wis; Quartz diabases, Sharpless, Mich., 1892, pp. 134-141; Pigeon Point Gabbro, Bayley, p. 61, and Jour. Geol. I, p. 712; porphyrite 15533, ophite 15523.
Olivine gabbro and diabase, Birch Lake, Minn., A. N. Winchell, Am. Jour. Sci., 1900, p. 374.
Typical Keweenawan melaphyres are just about on line between Hessose and Auvergnose.

CLASS III. Salfemane and (subclass 1) salfemone, with one doubtful exception[39] also *all of Order* 5, i. e, Quartz 1 : 7 feldspar, *all 4* dosodic or presodic.
Rang 3. Alkalic calcic.

Order 4. Vaalare quartz > 1-7 but 3-5 feldspar.
Vaalase and *Vaalose* diabase granophyrite, i. e. quartz diabase, Sharpless, 1892, p. 134.

Rang (2 or) 3.
Subrang 4. (*Kilauose*) *Camptonose.*
Ashbed diabase Bed 65, Eagle River, Steiger for A. N. Winchell. Jour. Geol. 1908, p. 772.
Rang 3. Duluth orthoclase gabbro *basic part* by A, N, Winchell and bottom of Bed 87, Eagle River. Cf. andose by Steiger.
Rang 4. *Auvergnose* most common type ophites "dry eutectic"?, Mt. Bohemia, St. Mary's Core, Greenstone by Steiger, and Duluth Troctolite for A. N. Winchell, J. G., 1900, p. 374; lower part Bed 64 (? Pumpelly), Lighthouse Point and other diabases.

CLASS IV. Dofemane. feldspar < 3 - 5 but > 1 - 7 - 1 - 1 of rock.
Subclass 1. P(yroxene), O (livine) M (agnetite) > 7 - 1 - 1 of rock (patite.)

Order 1. Hungarare Pyroxene and Olivine 7 > iron ores, Minnesotiare.
Rang 1. Permirlic, CaO + MgO + FeO > 7 Na_2O.
Section 1 Permiric MgO + FeO > 7 CaO.
Subrang 2. Domagnesic. MgO : FeO < 7 > 5-3.
Cookose. Hypersthene gabbro by Stokes for Bayley 7036.

(2.) *Osann's Chemical Classification*. It may be advisable also to give some account of the latest and most elaborate German classification, especially as Prof. A. Osann of Freiburg, the author, has named one of his types of gabbro the *Keweenaw type*, although curiously enough by some oversight, analyses 159 and 160 which are the same as 8786 and 8589 of Bayley's paper[40] are not really "from the Keweenaw peninsula," but rather from the Keweenawan of Minnesota.[41]

Professor Osann's chemical classification is found in a series of papers.[42] For his purpose he divides the analyses of the rock up into molecules. This is, indeed, the method adopted by almost all writers treating of the subject. He excludes the water and carbon dioxide as probably secondary, then adding up the figures obtained by dividing the percentage of the molecular weights of the different molecules obtains a number which is usually not far from 1.5. Dividing by this number and multiplying by 100 one obtains numbers which represent the percentages of the different molecules or atomic groups into which the rock may be divided. The silica, with whatever little titanium and zircon may be there, he represents by a small s, the alkalis, mainly; soda and potash by A. Subtracting from the alumina an amount equal to the alkalis gives a residue which is supposed to be combined with lime. It is called C. The balance of the lime and all the rest of the molecules of elements not already mentioned are grouped as F. Inasmuch as to every molecule of alkalis and all the molecule C there is a molecule of alumina as well as one of base, we find that all the molecules of the rock may be summed up in the expression $s+2A+2C+F=100$. Then for plotting he used trilinear coordinates like those of Fig. 13 and a, c, f, which stand in the same relation to each other as A : C : F. but are diminished so that $a+c+f=20$. He also uses two other symbols. Of these n is the ratio of soda to potash. Finally if we suppose that the molecule A is all used up in orthoclase or albite (Na, K) $Al\ Si_3\ O_8$, and the molecule C in anorthite $Ca\ Al\ Si_2\ O_8$, and that the rest of the molecules have at least one of silica we find that it will take $6A+2C+F$ of silica to combine with these other molecules in the various minerals. This, however, is not in reality strictly the case, for in most rocks there is some iron combined as hematite and magnetite. Nevertheless the ratio of the amount of silica present to the sum given gives one a pretty fair idea whether the silica is much more or much less than the amount required to turn basic molecules into the minerals of the silicate family in which they most naturally occur. Consequently he denotes the ratio of $s:6A+2C+F$ by k. It will be recognized at once that there is a certain general resemblance in Osann's and the Quantitative Classification. Roughly speaking, f and F will be proportional to the femic constituents of the Quantitative Classification; k will have some relation to the different orders of the chemical classification. The ratio of A:C corresponds to the rangs therein and the ratio n to the subrangs. The dominant type of the Keweenawan basic rocks, which is also by far the most wide spread, is what Osann calls the Keweenawan gabbro type. The type formula (Fig. 13) he gives $s_{51}\ a_1\ c_5\ f_{14}$. For Bayley's analysis 8786,—the normal gabbro which is so wide spread in Minnesota,—the formula

is $s_{50\cdot80}\ A_{2\cdot45}\ C_{11\cdot00}\ F_{22\cdot21}\ a_{1\cdot5}\ c_6\ f_{12\cdot5}\ n_{9\cdot1}$.

It is interesting to notice how closely this corresponds to the formula of the backbone of Keweenawan Point,—the Greenstone and the St. Mary's core ophite (Sp. 20618, Pl. VI) is not very far from the Keweenawan type, being $s_{52\cdot2}\ a_{2\cdot3}\ c_{6\cdot5}\ f_{11\cdot13}$. His effusive types that have a and f similar, like the Rogat or Macomer type have slightly more silica.

Of course, all these different classifications, while they have value as systems of pigeon-holes enabling us to find similar analyses by different authors, have back of them also the desire to express the chemical relationships and these can often be best given graphically. (Figs. 12 and 13.) Other methods of writing the composition of a rock in condensed form have been proposed notably by Levy and Becker. Some of Levy's are exceptionally ingenious but as the forms are rather complex for the printer I have omitted to summarize them here. The use of diagrams to express the composition of the igneous rocks has also been a matter of development. Probably the best plan is that of Brögger as modified by Levy, Hobbs and Iddings. Both Iddings and Osann also express the chemical relation of the rock by reference to a system of co-ordinates (Figs. 12 and 13) and then to express the minor factors Iddings adds a diagram whose center is determined by the co-ordinates. Almost all such attempts use the silica, which is the largest constituent in all the rocks we are considering, as abscissa. Iddings uses the molecular ratio of alkalis to silica for the ordinate. The position of some of the Keweenawan rocks on Idding's plan is shown in Fig. 12.

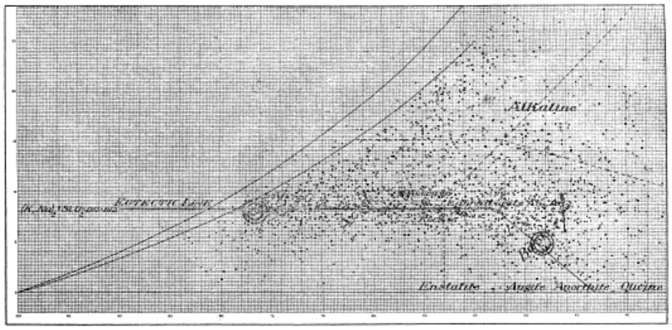


Figure 12. Diagram 45 from Iddings. See also Jour. Geol. Vol. 12, page 91. The abscissa are percentage of silica running down to the right. The ordinates are the ratios of the molecules of alkali to the molecules of silica. Dots represent numerous analyses collected by Iddings. The double circles have for their centers respectively the normal trachytic and normal pyroxenic magma of Bunsen. The apex of the V marks the position of Vogt's quartz feldspar eutectic. The square marks the oligoclase aplite. The line near 46% silica connects the ratio for lime melaphyres or ophies with that for soda melaphyres.

It will be noticed that the commonest types, the ophites, are not very far from the central values given by the diagram.

Osann in his diagrams (cf. Fig. 13) locates the position of the dot representing the rock by the ratio of A:C:F. In both diagrams the granites are found in the lower left hand part but in Osann's diagrams the extremely femic rocks are at the top whereas in Idding's diagrams they are at the lower right corner. The divergence of what may be called extra alkaline rocks from normal alkaline rocks is not as well shown, perhaps, in Osann's diagrams.

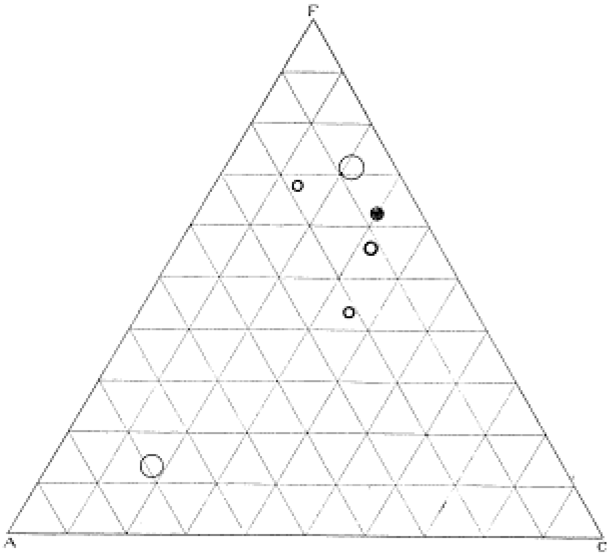


Figure 13. Illustrates Osann's method of plotting analyses and their relations to albite or orthoclase (Lower left hand corner A), anorthite (lower right hand corner C), ferro-magnesian minerals (at the vertex F). The center of the circle is determined by the ratio of A:C:F in the analysis. Given in order from apex they represent:

Bunsen's normal pyroxene magma.
Analysis of 15515, a sodic melaphyre.
Osann's Keweenawan type of gabbro.
A lime melaphyre or ophite. 20618.
The red rock of Mt. Bohemia described by F. E. Wright as an oligoclase gabbro aplite.
Bunsen's normal trachytic magma.

§ 5. FAMILY RELATIONSHIP OF KEWEENAWAN ROCKS.

The subject of consanguinity has been lately of much scientific interest. By consanguinity is meant the relationship between different rocks due to their derivation from the same molten mass. In studying the consanguinity of rocks it is best to group the analyses in some of the diagrams mentioned above, and determine which components vary most widely and the nature of the variations. We find that certain oxides are co-variants. They probably occur in one molecular compound in the rock magma. Other relations are relatively invariant throughout the group. The invariant relations are the marks of consanguinity. Still other oxides will be found to be complementary. The chemical differences between them in these cases may be due to the fact that one represents a part of the magma which crystallized before the other, due to its lower fusibility. Secondly, differences may be due to the settling of the heavier molecules under the action of gravity either before or after they crystallized out. This seems to account for the marked differences in composition in many of the lava flows where the lower part is darker and less feldspathic than upper parts. Thirdly, the differences may be. due to the absorption and solution of material from the adjacent rock, i. e., assimilation. I have often wondered if some of the melilite basalts were not produced thus, by the assimilation of limestone, since melilite is largely produced in the slags formed in smelting copper where limestone is added to the ground-up melaphyre. None of the Keweenawan rocks seem to have over 13 per cent of calcium oxide. The melilite rocks commonly exceed this. R. A. Daly has given us some most suggestive facts in this direction and, if we accept the results reached by Bayley, in fusion and absorption was the origin of some of the rocks at Pigeon Point—rocks not unlike those found at and near Mt. Bohemia.

One thing to which Harker[43] calls attention is well worth noting. If rocks have any such serial relationship, their relation can be expressed by a diagram (such as Fig. 14) in which some one constituent is taken as an ordinate and all the others as abscissas whose ends will form a continuous curve. If, for example, any series of rocks is made by different mixtures of two types, as for instance, Bunsen's normal trachytic and normal basaltic magma (Table 4, Nos. 1 and 3, Figs. 13 and 14) or if they are made by the gradual separation into two types, or if they are made by the solution of one kind of rock, say of quartzite, by one kind of magma, we should find fairly straight lines. If, on the other hand, more than two different kinds of rocks or splitting actions had been concerned, we should not find the same regularity. The mixtures of three rocks could, however, probably be expressed by a continuous surface.

It will appear from the tables of analyses[44] that, on the whole, the Keweenawan igneous rocks as shown by these analyses are consanguineous,—belong to one family which probably extends more widely than might at first be thought, since if we compare these analyses with analyses from the Cobalt region we find very great similarity. Among the characteristic features may be noted the following:[45] The soda dominates over ~the potash except in the extremely siliceous rocks and the potash is remarkably low. Free quartz is not abundant and so in classes 1, 2 and 3 rocks of order 5 dominate rather than 4. There is no extra aluminous rock such, that the alumina can not be combined with the alkalis and lime nor are there any ultra alkaline rocks. The *iron is decidedly high.* Is this connected with absorption from the iron formations beneath? In many respects they approach pretty closely the normal series described by Bunsen. There is some reason for believing that a certain amount of strontium is rather characteristic among the rarer bases. This is suggested not by the analyses, but by the fact that Lake Superior water contains strontium and that strontium, sulphates seem to be widely distributed in some of the later formations of the region.

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[38] Journal of Geology, Vol. 16, No. 8, Dec. 1908, p. 765. U. S. G. S. Monog. 52, p. 395.

[39] A slight increase in alumina, within limits of analytical error would bring it into Order 5 and perhaps into the Hessoses.

[40] Journal of Geology, Vol. 1, p. 712.

[41] Journal of Geology, Vol. XVI, p. 774.

[42] Tschermak's Mineralog. und petrographische Mittheilungen. XIX, XX, and XXI.

A notable thing is that the commonest type is the auvergnose and perhaps no rock is known which contains less silica and alkalis. Thus Iddings' statement that in general the" commonest rocks are like the average of all known rocks," certainly does not apply to the Keweenawan group. Perhaps we might connect with this another fact, that practically none of the iron and magnesia has been concentrated by differentiation into ultra basic rocks. A correlated fact is that although the analyses are all above the line (Fig. 12), I suggested as the eutectic trough for the ratio of alkalis to silica, ultra alkaline nephelitic Keweenawan rocks are almost unknown. The acmite syenite cutting the Virginia slates[46] and possibly the rocks referred to by Adams[47] are the nearest to exceptions. Occasionally an analysis may (like Bed 87 of the Eagle River section) figure out a little nephelme, but I have never recognized any, though secondary analcite occurs. Now it is suggestive that while the Keweenawan analyses come above this line which I suggest as somewhere near the eutectic line, in the commonest or auvergnose type there is little tendency to porphyritic texture. Nor is there much difference apparently in the age of the different constituents. The augite is commonly the last, yet only slight difference in composition seems to make a difference in the order of formation of the different ingredients. At any rate there is an overlap in their formation. Of the three principal ingredients, labradorite, magnetite and augite the labradorite is the first to form, the augite the last in the flows and smaller dikes, while in deeper intrusives where mineralizers had a part to play the order becomes very obscure. We may connect this, as I mention later, with the retention or loss of some mineralizer which like water has a strong tendency to keep silica in solution. But while the Keweenawan family magma seems to stand on the sodic side of the eutectic line or valley, it can not be far from it, since we do not find any ultra alkaline rocks nor is the total proportion of alkaline or acid rocks at all great compared with the volume of the average auvergnose. The" Keweenawan family magma may then be characterized as anchi-eutectic, using Vogt's term, but slightly more sodic than the eutectic and super-heated. While it hardly seems wise to go into extensive comparison of similar rocks which are wide spread, yet it does seem worth while to call attention to the fact, as others have done before, that the Post-Huronian intrusives which have played such a part in the mineralization around Cobalt and Sudbury in Canada, not only seem to be of the same age as the Keweenawan but of the same general chemical type (as may be seen by comparing a page of analyses of them from Gowganda which I owe to Mr. Bowen and from the Sudbury regions which is taken from Coleman and Walker's papers.[48]

The eutectic line[49] of Figure 12, it may be remembered, I suggested as perhaps one of balance between the alkalis and silica (in the presence of other bases also and probably water), for it is a well-known fact that the alkalis help to keep silica in solution. It is probably not located with great accuracy and indeed must vary with the proportions of other molecules, but the grouping of analyses, collected with no such thought by Iddings, seemed to show quite plainly that the dots representing rocks were arranged along such a line or trough especially toward the more siliceous end. Now, if the line as shown in the diagram (Fig. 12) does represent with some approach to truth the hypertectic or eutectic trough it means that a rock magma which has more silica in proportion to its alkalis than those represented by the points on the line would on the whole have an excess of silica. In early crystallization from such a magma solution we might expect that silica would be removed either by itself as quartz or combined with some other base than alkalis—and supposing that base to be magnesia or lime which was in excess, the silica also being in excess, the base could easily have all that it could readily hold. We should, therefore, be liable to have diopside or enstatite formed or $RSiO_3$ rather than some one of the bisilicates. As a matter of fact there does seem to be a tendency for rocks which have early crystals,—rhyocrystals,—of enstatite, hypersthene or diopside, to have analyses, points corresponding to which fall below the line. For instance I took all of Washington's[50] analyses indexed under andesite, porphyrite, and diabase, with a few of dacite, in which the author in naming the rock had prefixed enstatite, bronzite or hypersthene, and determined their position in the diagram. Out of forty-three, thirty-three fell below; the line, four on the line or just above it, leaving six only as possible exceptions. Without discussing here whether these apparent exceptions are due to analytical or other errors, are due to brotocrystals, to enclosures of bronzite, or are real exceptions for magmas of peculiar composition, it is plain that on the whole this test seems favorable to the line being located approximately. It should also be expected that in such rocks with plenty of SiO_2 there should not be so much of a tendency to form $FeO\ Fe_2O_3$ as $FeO\ SiO_2$ and Fe_2O_3. This may also be true and would give them a red appearance. On the other hand, if a magnesian base existed in excess and was ready to crystallize and the silica was deficient with regard to the alkalis the tendency then would naturally be that the base would take as little silica with it in crystallizing as it could, so that we should find olivine ($2MgO\ SiCO_2$ instead of enstatite ($MgO\ SiO_3$) as the rhyocrystal formed. Now, it is characteristic of the Keweenawan rocks, so far as I know them, that the porphyritic femic rhyocrystals are almost without exception olivine, and never enstatite and very often a feldspar more alkaline than labradorite. This is entirely in harmony with, the position of the Keweenawan analyses above the eutectic trough as shown in Figure 12.

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[43] "Natural History of Igneous Rocks," p. 118.

[44] On September 2, 1910, after this report was written (in Science XXXII, p. 313) F. F. Grout published some excellent analyses of the Minnesota Keweenawan. The reader is earnestly requested to refer to them, finding in Grout's No. 4 a typical ophite—10% lime melaphyre, and in No. 7 an average of Keweenawan rocks, which curiously has the same percentage of copper shown by the dark-Montreal sludge analyses. Grout also gives analyses of a number of minerals, of which the chloritic minerals are of especial interest.

§ 6. MAGMATIC CONCENTRATION.

Concentration due to changes that go on before the liquid rock has solidified is called magmatic concentration. There may be a settling of heavier, earlier formed crystals under gravity. To some such action Winchell’s plagioclasytes on the one hand and therefore iron ores on the other may be due.

On the other hand, if in part of the fluid some constituent crystallizes out owing to lower temperature, less gases, or any other cause there may be a migration of the substance which has been thus excreted from other parts of the fluid. Just so in the manufacture of artificial ice some salts will be found concentrated in the residual water, others not. Two forms of this I have called wet and dry differentiation.

§ 7. WET AND DRY DIFFERENTIATION WITHIN THE FAMILY.

Along the alkali-silica trough or eutectic line above mentioned (Fig. 12) there must be a tertiary eutectic or direction of crystallization as between the femic constituents and the alkalis .and silica, and that I have suggested[51] is probably near Bunsen's normal pyroxenic magma, as, shown in the figures (Figs. 12 and 13), in case no mineralizer is present, while in case mineralizer is present, as micropegmatite shows, the tendency is to crystallize out nearly all the femic constituents at temperatures probably above 800°C., while the quartz and feldspar remain in solution to be deposited as pegmatite between 800° and 550° or lower yet. Rocks lying along the eutectic trough will not differentiate so readily in ratio of silica to alkalis. But if silica was dissolved, as at Pigeon Point, or if water were lost, there would naturally be a shift in the eutectic line or valley trough. More particularly would a loss of Water make it tilt down at the less siliceous end, and shift the axis of the valley from the silica axis. We know, moreover, that a rock like A. N. Winchell’s plagioclasyte may crystallize at high temperatures leaving a more fusible femic remnant. Thus there might readily be differentiation in the direction of the eutectic line or trough without much variation in alkali-silica ratio. Just this we seem to have in the transition rocks (SS. 17033,17007,17037) just under (16951) the Mount Houghton felsite, as well as in the separation of the plagioclasyte of A. N. Winchell where a lighter feldspathic part may be conceived to have risen to the top while still keeping close to the SiO_2 :Na_2O = 12:1 ratio. But we find variations of composition in more than one direction. In the first place we find variation in composition by which the top is more sodic than the center or bottom where there is more (augite) lime in many flows, e. g., Isle Royale, SS. 15515-15523. This may, in part, be due to the crystallization at an early date of the feldspar and its rising to the top, but there are some reasons for believing that it may have taken place partly in the fluid state. The same general type of differentiation, for example, seems to connect analyses of different flows and the so-called Ashbed diabase or Tobin porphyrite type seems to stand in the same relation to the ordinary ophites as the top of a flow sometimes! stands to the bottom of the same.[52] Secondly, in connection with some of the gabbros we have a group of *red rocks*—gabbro aplites or syenites—which in some respects resemble the differentiation above described, but which also differ in that the silica runs up. This does; not occur in the first type of differentiation. One may very readily connect this increase of silica with the concentration of some mineralizer which like water tends to promote so markedly the solubility of silica.

Finally, we have ordinary felsites in which not only does the silica increase but also the potash. While these seem comparable in many respects with the segregation which has gone on at the center of Lawson’s quartz diabase dikes, the Pigeon Point rocks, however, are, according to Bayley, partly redissolved arkoses and it is a fair question whether the potassac felsites which occur in the Keweenawan may not be possibly the products of solution of some of the Huronian feldspathic quartzites, originally full of water. Such a solution would in any case be probably selective and one would not expect the original rock and the fused rock to be exactly the same in composition.

One thing seems to be fairly well made out. The felsites as an acid rock do not occur at random on Keweenaw Point but appear to be more or less associated with two definite horizons, one of them coming above the greatest and most extensive flow of the whole—the Greenstone. This felsite seems to have the focus of its distribution in the Porcupine mountains. A second group of felsites, that of Mt. Houghton, occurs much lower down, somewhere in the horizon of Conglomerates 6 and 8. Felsite outbursts seem to be associated with a temporary stoppage of volcanic activity shown by conglomerates after a big paroxysm leading to thick flows of basic lavas. A question which cannot be answered decidedly vet, is the relation between the differentiation that leads to the gabbro-aplite type of rock and that leading to the felsite. Is it possible that the gabbro aplites are only a half-way step toward the differentiation of the felsites? The relationship is certainly not serial because the soda increase is checked when we pass on toward the felsite and the potash becomes much more prominent.

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[45] Compare especially with the group analyses 40 and 41 of Daly (Proc. Am. Ac. Arts and Sciences, Vol. XVL (1910) p. 224).

[46] Report for 1908, p. 394. Also Winchell, M. H. Proc. L. S., M. J.

[47] Journal of Geology, VIII, (1900) p. 322.

[48] Omitted. See Bowen's paper, Journal of Canadian Mining Institute, 1909, p. 517. See also R. E. Hore, J. G. 1910, p. 274. T. L. Walker, Q. J. Geol. Soc. LIII (1897) pp. 56, and 63. A. P. Coleman, Jour. Geol. XV (1907) pp. 770-782.

[49] Or trough. If on Fig. 12 perpendicular to the paper lines to represent fusibility were erected, the surface joining the upper ends of the lines should have a valley or trough along that line.

[50] Analyses of igneous rocks, U. S. Geol. Survey Professional Paper No. 14, 1903.

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[51] Tufts College Studies, Vol. III, No. 1, p. 40.

[52] Tables 12 to 15.

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§ 8. SECONDARY CHEMICAL CHANGES.

Another interesting question pertains to the metamorphosis or change of the rocks after consolidation. No sharp line can be drawn here between the final consolidation and a work of change which at once begins. Judging by all we know the lava will be a solid rock at something not far below 900°C. and the quartz will not crystallize above 800°C., and most of the quartz of the felsites and quartz diabases was probably formed between 80G°C. and 550 °C., some possibly below 550°C. Many of the zeolites were formed at high temperatures. The radial coatings of chalcedony and chlorite which line interstices in some cases, especially in what I have called the doleritic texture, seem not to have replaced any other mineral, but to be deposited from the hot waters or gases which occupied the last interstices when the rock cooled off. An ordinary lava allowed to cool and crystallize thoroughly has the same porous or miarolitic texture that a mass of loaf sugar does, and this miarolitic texture or primary porosity gives opportunity for a range of reactions which may be called pneumatolytic. The presence of chlorite is particularly universal in our Michigan melaphyres. It will ordinarily be counted as secondary and yet we know very little regarding the real meaning of the chlorite— when it was formed and to what conditions its occurrence points. It may be pneumatolytic. I say "know" because though I make certain inferences and suggestions as to its probable role yet we cannot consider them as proven until the chlorite itself has been produced under them. It is of the more importance to us who are interested in the origin of copper because the chlorite is very intimately associated with the copper, and the copper often replaces it.

A curious feature is that the mine waters contain practically no magnesium whatever and one is reminded of some experiments by T. Sterry Hunt[53] in which he found a very strong tendency in *hot water* for calcium chloride to replace the magnesium chloride. He also found silicate of magnesium deposited.

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[53] Chemical and Geological Essays, pp. 122, 138, 151.

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§ 9. HYDRATION YIELDING NATIVE COPPER.

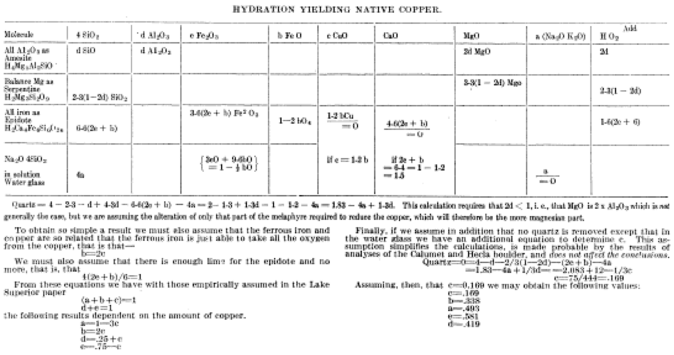
In my paper before the Lake Superior Mining Institute[54] I suggested that the formation of native copper could be chemically conceived without going outside the formation by assuming a small hydration of the melaphyre and a change of ferric to ferrous iron, and, as a printer not used to such formulae got them confused, I wish to repeat them! here. I assumed for the composition of the melaphyre a formula as follows:

CaO MgO (aNaO, bFeO, cCuO) (dFe_2O_3, eAl_2O_3) $4SiO_2$

and, as I said, (a+b+c)=1, and

(d+e)=1 often nearly,

if, now, we assume the melaphyre changed into chlorite, epidote, quartz, copper and water glass we have the following result:



HYDRATION YIELDING NATIVE COPPER.

Molecule	$4 SiO_2$	$d Al_2O_3$	$e Fe_2O_3$	b Fe O	c CuO	CaO	MgO	a (Na_2O K_2O)	Add H_2O
All Al_2O_3 as Amesite $H_4Mg_2Al_2SiO$	d SiO	$d Al_2O_3$					2d MgO		2d
Balance Mg as Serpentine $H_4Mg_3Si_2O_9$	2-3(1−2d) SiO_2						3-3(1 − 2d) Mgo		2-3(1 − 2d)
All iron as Epidote $H_2Ca_4Fe_6Si_6O_{26}$	6-6(2e + b)		3-6(2e + b) Fe^2O_3	1—2 bO_4	1-2 bCu =0	4-6(2e + b) =0			1-6(2e + 6)
Na_2O $4SiO_2$ in solution Water glass	4a		{3e0 + 9.6b0 = 1 − ½ bO}		if c = 1-2 b	if 2e + b = 6-4 = 1 − 1-2 = 1.5		a =0	

Quartz = 4 − 2-3 − d + 4-3d − 6-6(2e + b) − 4a = 2 − 1-3 + 1-3d − 1 − 1-2 − 4a = 1.83 − 4a + 1-3d. This calculation requires that 2d < 1, i. e., that MgO is 2 x Al_2O_3 which is not generally the case, but we are assuming the alteration of only that part of the melaphyre required to reduce the copper, which will therefore be the more magnesian part.

To obtain so simple a result we must also assume that the ferrous iron and copper are so related that the ferrous iron is just able to take all the oxygen from the copper, that is that—

b=2c

We must also assume that there is enough lime for the epidote and no more, that is, that

4(2e + b)/6=1

From these equations we have with those empirically assumed in the Lake Superior paper

(a + b + c)=1

d+e=1

the following results dependent on the amount of copper.

a=1—3c

b=2c

d=.25+c

e=.75—c

Finally, if we assume in addition that no quartz is removed except that in the water glass we have an additional equation to determine c. This assumption simplifies the calculations, is made probable by the results of analyses of the Calumet and Hecla boulder, and *does not affect the conclusions.*

Quartz=0=4—d—2/3(1—2d)—(2e + b)—4a

=1.83—4a + 1/3d= −2.083 + 12=1/3c

c=75/444=.169

Assuming, then, that c=0.169 we may obtain the following values:

c=.169

b=.338

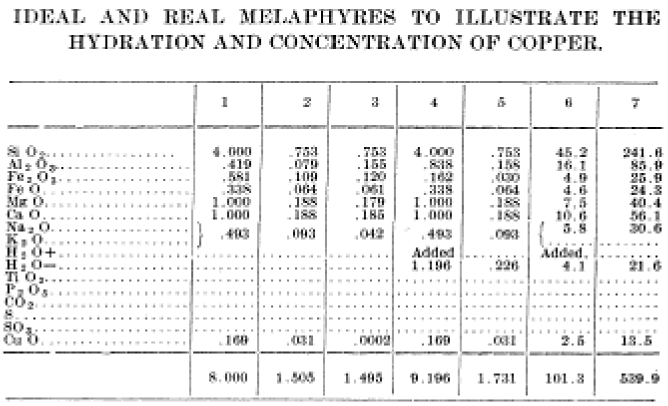
a=.493

e=.581

d=.419

The ideal melaphyre in this case will have the molecular proportions of Column 1 below. Comparing it (reducing the silica to the same amount Column 2) with the molecules of an ophite (Table XV, Analysis 5, Column 3) we notice that the alumina is low, and we can make the melaphyre more like our Keweenawan melaphyres and at the same time the epidote more like a normal epidote by supposing that e instead of being Fe_2 O_3 was largely Al_2 O_3. Transferring then .419 molecules from femic iron to alumina we get the results of Column 4. Column 5 is 4 made comparable with Columns 2 and 3 by making the silica the same. Multiplying by the molecular weights we get the percentage's (nearly) given in Column 6. In this column the water is supposed to have been added to the 97.2 melaphyre, but may have been present originally in interstices. If for instance, the specific weight of the fresh lava was 2.88 (2.88 tons to the cubic meter) then 97.2 tons of it could occupy about 33.7 cubic meters, and the total space occupied would be 37.8 cubic meters of which space 11 per cent would be occupied by water. The original specific gravity of the whole would be 101.3/37.8=2.68.

While this process may account for small specks of native copper found in the doleritic interstices, I do not suppose that the great masses have been collected so simply.



IDEAL AND REAL MELAPHYRES TO ILLUSTRATE THE HYDRATION AND CONCENTRATION OF COPPER.

	1	2	3	4	5	6	7
SiO_2	4.000	.753	.753	4.000	.753	45.2	241.6
Al_2O_3	.419	.079	.155	.838	.158	16.1	85.9
Fe_2O_3	.581	.109	.120	.162	.030	4.9	25.9
FeO	.338	.064	.061	.338	.064	4.6	24.3
MgO	1.000	.188	.179	1.000	.188	7.5	40.4
CaO	1.000	.188	.185	1.000	.188	10.6	56.1
Na_2O	.493	.093	.042	.493	.093	5.8	30.6
K_2O							....
H_2O+	....	....	....	Added	....	Added.	....
H_2O-	....	....	....	1.196	.226	4.1	21.6
TiO_2	....	....	....	....	....	....	....
P_2O_5	....	....	....	....	....	....	....
CO_2	....	....	....	....	....	....	....
S	....	....	....	....	....	....	....
SO_3	....	....	....	....	....	....	....
CuO	.169	.031	.0002	.169	.031	2.5	13.5
	8.000	1.505	1.495	9.196	1.731	101.3	539.9

1. Ideal melaphyre after formula above, using numerical values found for a, b, c, d and e.
2. Same as No. 1 divided by 4/.7S3.
3. Real melaphyre for comparison.
4. Ideal melaphyre with adjusted alumina.
5. No. 4 divided by 4/.753.
6. Ideal cupriferous melaphyre in per cents.
7. No. 4 multiplied by molecular weights.

§ 10. ALTERATION OF CALUMET AND HECLA BOULDER.

In his chapter on the paragensis of the minerals associated with copper[55] Pumpelly gives a full account of "replacement of porphyry matrix by chlorite and copper" as follows:

"Among the pebbles in the Calumet conglomerate there is a variety of quartz porphyry, with a brown, compact, almost jaspery matrix, which only glazes slightly before the blowpipe. In this paste there are numerous grains of dark quartz 1/20 to 1/4 inch in diameter, and often more frequent crystals of flesh red feldspar, apparently orthoclase,—1/10 to 7/10 inch in length.

"It not rarely happens, that in these flesh red crystals there appear dirty green portions exhibiting the twin-striation of a triclinic variety. The feldspar is hard and brilliant, but is nevertheless no longer intact; under the glass the crystals appear cavernous, 10 per cent or more of the substance being gone. This is the character of this porphyry in the freshest pebbles.

"I have before me a pebble 4 inches in diameter, broken through the middle. It was the same variety of porphyry I have just described—the same brown matrix, with the same grains of quartz, and the same large crystals of orthoclase, often enclosing crystals of triclinic feldspar. But this pebble carries on its face the history of an extreme change. In the interior, where it is freshest, the matrix, still of the same brown color, has become so soft as to be easily scratched with the point of a needle. The quartz grains are highly fissured, and the surfaces of the fissures are covered with a soft, light-green magnesian mineral. The feldspar, although it still resists the point of the steel needle, has generally lost its glance, and has an almost earthy fracture; it is lighter colored, and tends to spotted dirty-red and white. In places, specks of chlorite are visible in the holes in the altered feldspar, and the cleavage planes often glisten with flakes of copper. As we go farther from the middle of the specimen toward the original surface of the pebble, the matrix becomes much softer, though still with brown color and brown streak, and then changes to a soft, green chloritic mineral, which whitens before the blowpipe, and fuses on the edges to a gray glass. A little farther from the center there is no longer a trace of the porphyry matrix, it is altered wholly to chlorite. The feldspar crystals are somewhat more altered here than they are in the middle of the pebble, but the quartz grains seem to have been in part replaced by chlorite. The change to chlorite is accompanied throughout by the presence of a large amount of copper. While in the interior of the pebble, the flakes of copper are confined to the cleavage planes of the feldspar, and the porphyry matrix exhibits scarcely a trace of the metal, the chlorite which has replaced the matrix contains in different parts of the specimen from 10 to 60 per cent, by weight, of copper.

"In another pebble of the same porphyry, not only is the original matrix gone, but the usurping chlorite has been almost, if not wholly, replaced by copper; and we have as the remarkable result a quartz porphyry whose crystals of feldspar and grains of quartz lie in a matrix of metallic copper. There is still a very small amount of chlorite present, but it seems to have come from the change of the feldspar crystals and quartz grains.

"In other pebbles of the same quartz porphyry, containing, perhaps, less quartz, the alteration seems to have taken a somewhat different direction, or at least the result before us is different. In the interior of the pebble, the matrix is of a darker and dirtier brown than in the previous cases, which may be due to the presence of manganese in the alteration product. Going from the middle, the brown color changes rather abruptly to a dirty greenish-grey; the material also becomes softer, but it is earthy, with an earthy odor, and gritty to the touch. The change seems here to be in the direction of kaolinization.

"The entire pebble is permeated with minute shining threads and plates of carbonate of lime. The lighter colored portion contains considerable copper, while nearer the surface of the pebble it is largely replaced by that metal. Pebbles showing the various alterations described above are by no means rare. Many of them, from 1 inch to 1 foot in diameter, are found every day."

In Economic Geology, Volume IV, Number 2, pages 158-173, I gave a description and analysis of a boulder of the Calumet and Hecla conglomerate which was being replaced by copper. It was originally some sort of a porphyry. Oligoclase phenocrysts remain embedded in it as were noted by Pumpelly.

Pumpelly's observations, minute for the time, were not, however, supplemented by chemical analyses. Two analyses of these boulders are presented in Table XVII. Side by side are placed analyses of country rocks comparatively little affected by alteration. Just what the original composition of one of these altered pebbles was is a question which one must be cautious in answering, but the general trend of change is unmistakable. Take, for instance, the partial analysis of a boulder by G. H.

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[54] Vol. XII, pp. 85-86; Vol. XIII, p. 148. The discussion in U. S. G. S. Monograph 52 with new analyses, pp 580-592, is especially valuable. The argument that the waters were hot is strong. I think that there is indication that they were also heating up, that is, circulating down into a mass of still hot rock. The analyses of vein and well rock at the Winona Mine (p. 583) seem to check very well with the formation of epidote assumed in this section.

Heath, chemist of the C. & H. Mining Co. This was a "bluish grey, greasy deposit like talc found inside a boulder," the outer shell of which was turned to copper. The partial analysis was:

Silica, SiO_2	36.75	= .612 molecule,
Alumina and Iron oxide { or as FeO)	24.57	= .294
Alumina and Iron oxide { (Fe_2O_3, Al_2O_3	27.34	
Magnesia, MgO	23.24	= .581
Loss on ignition H_2O; CO_2	11.07	= .616
Difference $Na_2O + K_2O$?	1.6	= .026?
	100.00	

This evidently corresponds closely to a formula $2H_2O$, 2MgO, FeO, $2SiO_2$ closely allied to that of serpentine. Serpentines are often derived from peridoites. There are, to be sure, peridotites known in the Lake Superior region, but it is most probable that the original rock was not more basic than an ophite, perhaps much more silicious.

Fortunately I was able, through the kindness of J. L. Nankervis, the commissioner of mineral statistics, to obtain another boulder of the kind in which enough of the texture was left and in particular large porphyritic crystals of oligoclase to make one reasonably sure that we are dealing with a porphyrite not so femic (rich in iron, magnesia, etc.) as the ophite but in composition between analyses 1 and 2 of Table XVII.

These peculiar boulders, yet after all at one time fairly common, which were so largely changed may have been somewhat exceptional in composition to begin with, but it is very probable, I think, that often they had originally over 60 per cent SiO_2.

DESCRIPTION OF BOULDER 20600.

This pebble or boulder (20600) as may be noted, is surrounded by a shell of copper considerably stained with carbonate, probably of recent origin. The interior next the outside is decomposed greyish-green or blanched. The main mass is mixed greenish and dark maroon, and shiny and soft. This soft (H=1) matter is the material analyzed. In it are embedded white Karlsbad-albite twins of andesite or oligoclase, one of which dug out shows P. (001), y. (201), M. (010) and the prism? (110).

While obscured with enclosures so that the refraction is not easy to determine, for one crystal it appears to be near and a little above 1.545. In another case it is distinctly near 1.536. The extinction angle on P against M is 3°—3°, in another case 7°—7° and generally small (in one case in that zone 10—15) ? (18°—18°).

The boulder tested by Heath had a very similar ground mass. Both the albite and Karlsbad twinning are plainly visible with the pocket lens. No quartz or orthoclase phenocrysts were noticed.

This kind of alteration attacking the ground mass is not, as Pumpelly says, uncommon. Capt. Joseph Pollard, of the Calumet and Hecla mine, has quite a collection of Karlsbad twins, picked out of the soft rock, that show the crystal form nicely. They are sometimes partly replaced by copper, and are sometimes an inch or more in size. Very suggestive also is a boulder in his collection which is a mere hollow shell, lined with red feldspar (orthoclase?) and specular iron ore (hematite). Another pebble which seems to have been originally calcite, and has a calcite core, is now largely replaced by specular ore (hematite) with a little copper.

Red felsite pebbles often have blanched borders.

From Heath's and Wilson's analyses (Table XVII) of boulders and these of the slime it is clear that water has been added. Either iron has increased or there is a greater loss of other constituents than is at all likely. Alumina is probably nearly constant,—appears to be so both in the slime analysis and in 20600. Magnesia certainly is no less and in Heath's boulder much more. Lime has probably increased. If the alumina is constant, the silica has been removed. It may be noted, too, that if we suppose Sp. 17033 to be the original of Sp. 20600 the amount of silica removed is in molecules about four times that of the alkalis. If we compare the fresh felsite with the conglomerate slime, it also seems likely that much more silica than alkalis is removed. We may say, then, roughly, that iron and water have been added and water glass abstracted. It may also be noted that whereas in 17039 the rate of alkalis to silica is more than 1:12, in the boulder it is in the proportion .043:.523. Possibly alkalis in excess of the eutectic are more easily removed.

A further thing to remark is that it is doubtful if there is any marked change from ferrous to ferric iron. Water glass removed ($Na_2Si_4O_9$) and serpentine introduced ($H_4Mg_3Si_2O_9$) have the same amount of oxygen. There is, however, an uncertainty in comparing a specimen from a deep mine with specimens exposed in outcrops and necessarily oxidized. It seems then quite safe to assert that the deposition of copper in the Calumet and Hecla conglomerate was one feature of a change which included also the removal of water glass and enrichment with water, magnesia and iron.

§ 11. KAOLINIZATION OF KEWEENAWAN DIKES.

An alteration in some respects similar in that water is absorbed and sodium silicate removed, but in some other respects quite different, is that of the kaolinization of the diabase dikes, evidently belonging to the Keweenawan, which is found near the iron ore bodies. These have been studied by Van Hise and Patton. Illustrative analyses are found in Table XVIII. Figure 15 gives the graphical results. In this figure the proportions of each ingredient are laid off along a horizontal line, but the length of the whole line is shortened in such a ratio that the length assigned to alumina appears constant. If the alumina really is constant, then Figure 15 gives the actual weights of each constituent remaining in an undisturbed volume of rock. Suppose the original specific gravity was 2.9, then in 13456 there was

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[55] Vol. I, pt. II, Chapter III, p. 37.

originally 100 tons of which originally 47.99 were silica. In the Aurora dike in a similar space there would be less than 19 tons of silica or 44 tons in all, more than half the dike having been removed.

A noteworthy fact is that the components are not removed at the same time in the same proportions. It appears probable that the rock is early hydrated up to a constant ratio with the alumina, that the soda and potash and the magnesia go first, the lime follows close after, the titanium oxide and silica persist. The ferrous iron either goes or is turned into ferric oxide. Later leaching removes the silica without changing the ratio of water to alumina after it reaches the proportion $2H_2O{:}1Al_2O_3$,—a rather noteworthy fact.

§ 12. CONCENTRATION IN SEDIMENTATION.

Another form of concentration is brought out by comparing the composition of the Keweenawan igneous rocks and the sediment which may have been derived from them.

Not many analyses have been made of the sedimentary rocks. One very obvious reason for not analyzing the conglomerates is that they vary so and the pebbles are so large that one would have to take a large sample in order to get any idea of what the average composition is. The analysis of crushed Calumet and Hecla conglomerate (1 of Table XIX) is much more basic than one would have thought. We have gathered the analyses given in Table XVII which will serve to give us some idea of the character of the sedimentary rocks and the kind of change they have undergone. No. 4 is a rock from "Siskowit Point" on Isle Royale.[56] This is from a series of dark maroon beds dipping at a high angle toward the lake. They are in all respects like the Freda sandstones. Comparing them with the basic igneous rocks we see the greater predominance of ferric iron. Comparing them with the felsites we see that there is also a greater amount of iron and of bases generally except soda and potash which must have been removed and deposited elsewhere. If we suppose these rocks not to have been derived from the felsites but from more basic rocks where the soda exceeds the potash then we must imagine at any rate a considerable addition of quartz and removal of lime. Rocks which are, however, much more likely from their looks and appearance to have been derived from the basic rocks are the so-called Nonesuch shales.[57] The analysis was of a dark grey, almost black rock which might easily be supposed to have been a bituminous rock, but is not. The dark color is due apparently to chlorite and iron oxide and some beds of the Nonesuch shale show minute scales of iron ores, etc., lying upon them and giving the bedding planes an appearance like the black sands of our present beaches.[58] The rock is also higher in alumina which is suggestive of chlorite. The alumina is just about the same as in one of the melaphyres but the silica is as much again and the iron oxides and other bases lower. The proportion of soda to potash. is very similar to that which we find in the melaphyre,—large for a sedimentary. The lime is largely removed. We have here, then, a rock composed partly of quartz (petrographic examination shows ordinary quartz sand) and partly of a decomposed melaphyre in which the bases, but especially the lime, falls much short. Another analysis; of Keweenawan sandstone is given by Sweet.[59] This rock lies between the Nonesuch shale and (Siskowit Point) Point Houghton rock in composition.

If we take the Calumet and Hecla slime, the Nonesuch shales, the Freda sandstone and Jacobsville sandstone we find a series fairly consecutive as to silica percentage, and as to ratio of potash to soda. The chloritic character of the Nonesuch is shown by an extra amount of alumina and magnesia. The soda also diminishes steadily.

The only way to get a fair idea of a rock like the Calumet and Hecla conglomerate or any other coarse conglomerate is to analyze a very large sample. The analysis of slime overflows from the trough classifiers between stamp-heads and jigs taken September, 1906, which I owe to Mr. J. B. Cooper, Superintendent of the Calumet Smelters[60] is the best representation I can give, though it contains not as much of the felsite material as I believe it should to truly represent the rock. A comparison of it with the Osceola amygdaloid slime, however, shows pretty clearly the kind of rock to be expected with any given per cent of silica.

Comparing the Osceola slime with the various analyses of melaphyres we see that the water and alumina are relatively higher, but the iron and lime are not, the alkalis and soda are reduced.

Comparing the Calumet slime with felsite from which it may have been largely derived we again find water and alumina higher, silica and soda lower, lime, magnesia and iron on the whole higher, but rather irregularly distributed. In the conglomerate there is little or no sign of that characteristic sedimentary concentration which leads to a concentration of quartz. This certainly agrees with its brecciated and but little rehandled character.

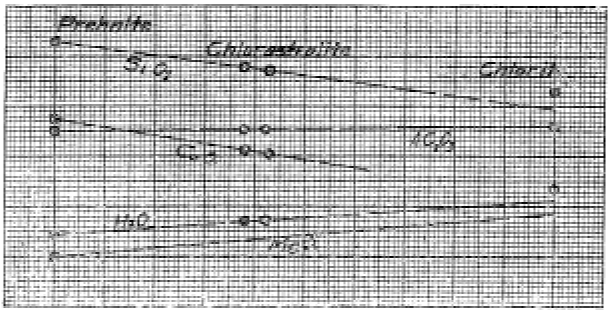

Figure 14. Illustrates relation of prehnite, chlorastrolite and chlorite. In this diagram the percentages of silica are the abscissa, while the other elements are shown by ordinates as indicated on the diagram.

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[56] Point Houghton, see Vol. VI, also Bull. 8, Minn. Sur. XXXIII, Ser. No. 165, Geol. Sur. No. 555, J. A. Dodge, analyst.

§ 13. CONCENTRATION OF CHLORITIC MATERIAL.

One of the commonest changes throughout the Keweenawan rocks is the development of chlorite or green earth material. It is universal. Chlorite first appears in interstices apparently once empty, coating them in concentric agate-like bands. It also occurs after augite and later feldspar. It coats the joints. As we have seen it seems to replace even the felsitic pebbles in the conglomerate. It also replaces the prehnite as has been well described by Pumpelly and as Hawes says chlorastrolite seems to be but a half-way house between prehnite and chlorite. This is shown by Figure 14.[61] In table XVI are grouped together some analyses of chloritic material. They vary a good deal and are very inaccurate, yet there is a plain tendency toward a composition containing about 30 per cent silica, 30 per cent alumina, 30 per cent ferrous iron or magnesia and 10 per cent water ($H_4Al_2FeSi_2O_{10}$), especially if one considers the probable character of the errors due to impurities. The gangue No. 5 may be considered as made up of about 40% silica + 60 % of (31% SiO_2 33% $Al_2O_3$20% FeO 2%MgO 13% H_2O).

§ 14. CONCLUSIONS.

One will find a marked similarity in many of the processes of secondary change above given. We may tabulate them thus:

	1	2	3	4	5	6
SiO_2	decrease	decrease	decrease	decrease	increase	decrease
Al_2O_3	increase?	increase?	increase	increase	increase	constant?
Fe_2O_3	increase	increase?	increase	increase?		decrease
FeO						decrease
MgO	increase	?	increase?	increase?		decrease
CaO			increase	decrease		decrease
Na_2O	decrease	decrease	decrease		decrease	
K_2O				?		decrease
H_2O—						
H_2O+	increase	increase	increase	increase	increase	increase

TABULATION OF CHANGES IN PROPORTIONS OF VARIOUS CONSTITUENTS.

The analyses upon which this table is based will be found in the other tables.

1. Calumet & Hecla boulder changed to chlorite.
2. Original rocks and Calumet & Hecla slime.
3. Ophite to Osceola slime.
4. Prehnite to chlorite.
5. Original igneous rocks to sediment.
6. Diabase dike to kaolinite.

But it is by no means necessary to infer that the change goes on pari passu for all ingredients. Quite the contrary. It seems as though the water were introduced first until the ratio was in percentages about 1 per cent of H_2O to 3 per cent of Al_2O_3, or in molecules about $2H_2O$ to lAl_2O_3. After this there is practically no further addition of H_2O,—the farther apparent gain being due to the subtraction of other ingredients?

The alkalis and the silica seem to be removed together. If they go off as water glass (Na_2O .$4SiO_2$) the per cent proportions will be 1 per cent Na_2O to $3.885SiO_2$. The ratios obtained by comparing the diabase porphyrite 17039 with the altered Calumet boulder (59.92—31.43/10.3—0.2) or the Calumet tailing with felsite (75.67—55.08/8.74—4.01?) are fairly harmonious and if we compare the Osceola amygdaloid tailings with some of the fresh or lime melaphyres, say the latest analysis of the Greenstone—we see that the ratio is similar within the limits of analytic error and variation in composition due to washing out the chlorite (47.69—41.31/2.44—0.04). The alkalis always escort off more than as much silica.

It is plainer from the looks than from the analyses that the ferrous iron is often, perhaps not always, largely changed to ferric iron, although that also appears in 20600. All the fresher melaphyres show large quantities of ferrous iron.

The role of the lime is least simple. Owing to the fact that before or in the process of crystallization there was a good deal of differentiation of lime it is harder to be sure what the percentage was originally and calcite may often have been introduced. In the salic rocks it seems to increase, being derived from the surrounding femic rocks. We may note the fact that the 10 to 12 per cent of lime that might have existed in a, fresh lime melaphyre—an ophite—seems not to be exceeded in alteration. There are many things which I have seen,—such as the replacement of a pebble of calcite in the Calumet and Hecla conglomerate by hematite, which surrounded it,—which lead me to feel sure that the trend of the lime is toward the calcite, epidote, and calcium chloride dissolved in the mine water, so that lime also is removed from the original rock unless epidote or calcite accumulates. While the magnesia and iron really tend to form chlorite, and this alteration is conspicuous in the

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[57] Analysis 2 of Table XIX, Core at 500 feet of White Pine Exploration, d 34.

[58] The palladium also suggests this.

[59] Geology of Wisconsin, Vol. Ill, p. 350.

[60] "Samples taken Sept. 1906. They fairly represent the rock material, except that the slimes contain a little larger proportion of the softer portion, limy constituents and less of ham gravel material.

"The best *average* sample of rock would be an average of all tailings for one to six months but such a sample "has never been assayed completely".

	Conglomerate %.	Amygdaloid. %.
Loss on ignition	5.02	7.89
Silica	55.08	41.31
Iron oxide, Fe_2O_3	9.04	12.90
Alumina, (+tr. TiO_2)	15.41	22.46
Lime (CaO)	7.02	11.08
Magnesium Oxide, (MgO)	2.49	4.07
Chlorine	.18	.11
Sulphur tri-oxide (SO_3)	.04	traces.
Copper, (may be part oxide)	1.70	.14
Traces of sodium & potassium not estimated	95.99	99.96

Copper in this sample is evidently high, for an average.

[61] See also Grout's paper in Science 1910, Vol. XXXII, p. 312, and U. S. G. S. Monog. 52, p. 582.

color change and under the microscope there is little sign of it in the analyses. The Osceola amygdaloid tailings: though relatively coarse had, however, no doubt lost some chlorite in washing. I have shown above that a small absorption of water without any other great change might make a great change to chlorite, but in the alteration of the Calumet and Hecla boulder and in the change of prehnite through chlorastrolite we must have, however, a real "metasomatic" action in which magnesia is actually introduced.

The chemistry of the mine waters and a further discussion of the chemistry of the copper deposition will be found in later chapters.

§ 15. DENSITY OBSERVATIONS.

The density of the rocks is generally given in connection with the chemical composition. Of this it is indeed a function. Yet it seems to have especial importance,—enough to warrant a brief treatment here, especially since many tests have been made of density apart from chemical analyses. Jackson's report[62] contains a large number of observations of density scattered through it and many of these are repeated in Foster and Whitney's report. They are tabulated below. In connection with the analyses which have been made from time to time tests of specific gravity have been made which are assembled in the tables.

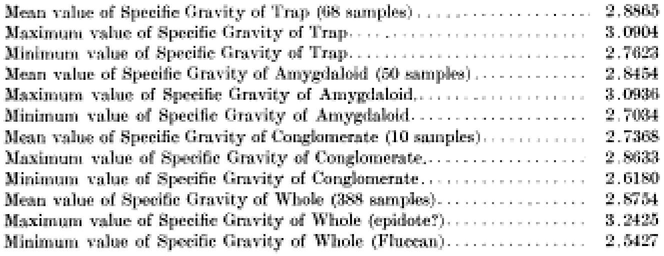
The most extensive work, however, is that which has been done by President F. W., McNair in connection with his determination of the density of the earth by the observations about the Tamarack shaft. I have not tried to abstract this work which is not yet published but a word of explanation may be of interest and serve to draw attention to it.

Any object vibrating before a source of attraction vibrates more or less rapidly according to the strength of the attraction. This can be readily tested with a compass needle and a magnet. It is also true of a pendulum attracted by the earth. The rate of vibration of the pendulum depends upon the attractive force of the earth. The strength of magnetic attraction may be measured by the Dip Compass in the same way. Now in the case of a pendulum swinging at the bottom of a deep shaft the pendulum is no longer attracted downward by the whole mass of the earth but only that part which is still beneath it and it will accordingly vibrate slower. Comparing the rapidity of vibration of the pendulum swinging at the bottom of the shaft with that at the top, one can compare the attractive force of the spheroid beneath the pendulum,—that is to say, an earth which has a radius about a mile shorter with the attraction of the whole, earth—and if we know the density of the intervening shell—that part within three or four miles around the shaft is the most important,—it becomes possible to estimate the density of the earth. In consequence President McNair had a large number of accurate sp. gr. tests made and he has kindly enabled me to cite the figures below. It will be noticed that the mean value of the specific gravity of the trap and of the amygdaloid is very nearly the same although the amygdaloid may possibly be two per cent less and that the numerous earlier observations of specific gravity from various places are not far from the values he obtained. This shows that his values are fairly representative not merely for the neighborhood of the Tamarack shaft but the formation as a whole. It is noticeable that whereas the amydaloid was originally a very bubbly, open and glassy rock, probably having very much less density than the trap, it is now all about the same density. On the whole it is much more altered. This increase in density will be, then, entirely consistent with the reactions above suggested which seem to have actually produced condensation. It is noteworthy, too, that while the conglomerate is somewhat lighter than the traps, it is rather heavier than one would think, for its specific gravity as compared with the quartz porphyries of which it is so largely composed is several per cent greater. This may be due to the very considerable presence of epidote in the lower and calcite in the upper levels which might make a difference in the specific gravity.

The minimum value of the specific gravities approaches very closely that of kaolin. It is conceivable that through zeolites a much less specific gravity might be obtained and the fact that no such specific gravity was obtained in the three hundred and eighty-eight samples shows that none of them contained any large amount of the lighter zeolites. These results are of considerable interest in connection with the question as to the effect of secondary chemical alteration. I think it may be fairly said that there is no very marked sign of expansion by hydration (although on the whole the mean specific gravity is somewhat less than most of the basalts whose specific gravities are given by Rosenbusch) for the mean value is just about that of the Breitfirst dolerite and the maximum value of the specimens and their range compare on the whole very closely. The basaltic glasses are distinctly lighter.

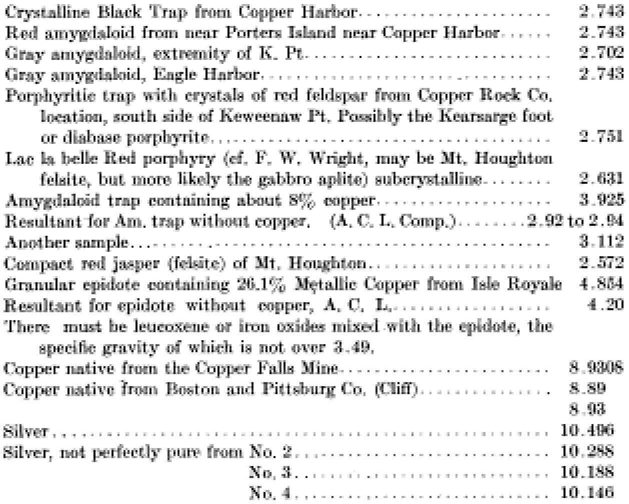
The mean density is, of course, a factor which comes in in numerous other calculations and is of practical value. It may be worth remembering that 1,000 ounces of water make a cubic foot, nearly enough for most practical uses, so that by multiplying the specific gravity of a rock by 1,000 you will get the weight in ounces of a cubic foot. The average weight of the Keweenawan traps is, therefore, about 2,880 ounces or 180 pounds per cubic foot.

The following are the data that I owe to the kindness of President F. W. McNair and Prof. James Fisher, Jr., of the Michigan College of Mines. They are derived from a very elaborate series of observations made near the Tamarack shaft in connection with President McNair's determinations of gravity. It was found with regard to the deeper samples that owing to the presence of calcium chloride no definite specific gravity could be found so that the accuracy of the fourth decimal place in individual samples was nil.



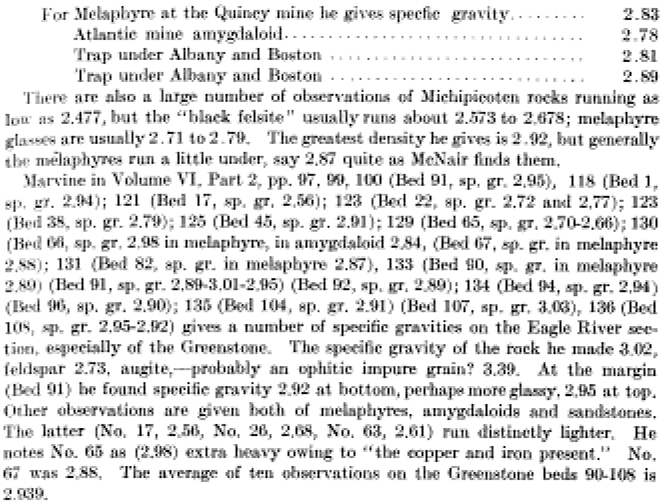
Mean value of Specific Gravity of Trap (68 samples)	2.8865
Maximum value of Specific Gravity of Trap	3.0904
Minimum value of Specific Gravity of Trap	2.7623
Mean value of Specific Gravity of Amygdaloid (50 samples)	2.8454
Maximum value of Specific Gravity of Amygdaloid	3.0936
Minimum value of Specific Gravity of Amygdaloid	2.7034
Mean value of Specific Gravity of Conglomerate (10 samples)	2.7368
Maximum value of Specific Gravity of Conglomerate	2.8633
Minimum value of Specific Gravity of Conglomerate	2.6180
Mean value of Specific Gravity of Whole (388 samples)	2.8754
Maximum value of Specific Gravity of Whole (epidote?)	3.2425
Minimum value of Specific Gravity of Whole (Fluccan)	2.5427

Jackson gives in his report (p. 495) the following specific gravities:



Crystalline Black Trap from Copper Harbor	2.743
Red amygdaloid from near Porters Island near Copper Harbor	2.743
Gray amygdaloid, extremity of K. Pt.	2.702
Gray amygdaloid, Eagle Harbor	2.743
Porphyritic trap with crystals of red feldspar from Copper Rock Co. location, south side of Keweenaw Pt. Possibly the Kearsarge foot or diabase porphyrite	2.751
Lac la belle Red porphyry (cf. F. W. Wright, may be Mt. Houghton felsite, but more likely the gabbro aplite) subcrystalline	2.631
Amygdaloid trap containing about 8% copper	3.925
Resultant for Am. trap without copper. (A. C. L. Comp.)	2.92 to 2.94
Another sample	3.112
Compact red jasper (felsite) of Mt. Houghton	2.572
Granular epidote containing 26.1% Metallic Copper from Isle Royale	4.854
Resultant for epidote without copper, A. C. L.	4.20
There must be leucoxene or iron oxides mixed with the epidote, the specific gravity of which is not over 3.49.	
Copper native from the Copper Falls Mine	8.9308
Copper native from Boston and Pittsburg Co. (Cliff)	8.89
	8.93
Silver	10.496
Silver, not perfectly pure from No. 2	10.288
No. 3	10.188
No. 4	10.146

Macfarlane in his report made extensive tests of specific gravities:[63]



For Melaphyre at the Quincy mine he gives specfic gravity	2.83
Atlantic mine amygdaloid	2.78
Trap under Albany and Boston	2.81
Trap under Albany and Boston	2.89

There are also a large number of observations of Michipicoten rocks running as low as 2.477, but the "black felsite" usually runs about 2.573 to 2.678; melaphyre glasses are usually 2.71 to 2.79. The greatest density he gives is 2.92, but generally the melaphyres run a little under, say 2,87 quite as McNair finds them.

Marvine in Volume VI, Part 2, pp. 97, 99, 100 (Bed 91, sp. gr. 2,95), 118 (Bed 1, sp. gr. 2,94); 121 (Bed 17, sp. gr. 2,56); 123 (Bed 22, sp. gr. 2.72 and 2,77); 123 (Bed 38, sp. gr. 2.79); 125 (Bed 45, sp. gr. 2.91); 129 (Bed 65, sp. gr. 2,70-2,66); 130 (Bed 66, sp. gr. 2,98 in melaphyre, in amygdaloid 2,84, (Bed 67, sp. gr. in melaphyre 2,88); 131 (Bed 82, sp. gr. in melaphyre 2.87), 133 (Bed 90, sp. gr. in melaphyre 2,89) (Bed 91, sp. gr. 2,89-3,01-2,95) (Bed 92, sp. gr. 2,89); 134 (Bed 94, sp. gr. 2,94) (Bed 96, sp. gr. 2,90); 135 (Bed 104, sp. gr. 2.91) (Bed 107, sp. gr. 3,03), 136 (Bed 108, sp. gr. 2.95-2,92) gives a number of specific gravities on the Eagle River section, especially of the Greenstone. The specific gravity of the rock he made 3,02, feldspar 2.73, augite,—probably an ophitic impure grain? 3,39. At the margin (Bed 91) he found specific gravity 2,92 at bottom, perhaps more glassy, 2,95 at top. Other observations are given both of melaphyres, amygdaloids and sandstones. The latter (No. 17, 2,56, No. 26, 2,68, No. 63, 2,61) run distinctly lighter. He notes No. 65 as (2,98) extra heavy owing to "the copper and iron present." No. 67 was 2,88. The average of ten observations on the Greenstone beds 90-108 is 2.939.

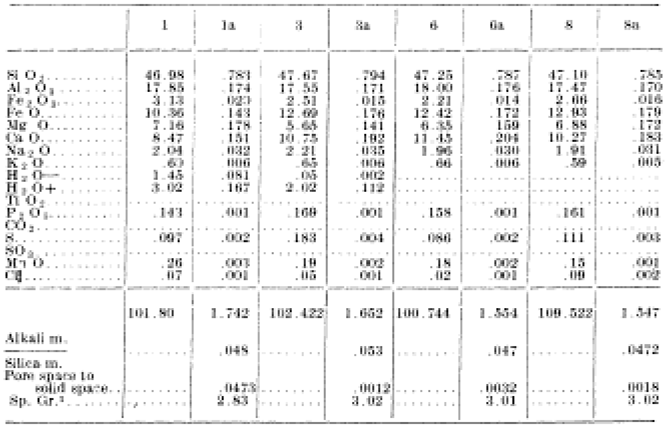
I do not find that Irving, Wadsworth, or Rominger paid much attention to specific gravities, as microscropic methods of determining the rocks were superseding them.

While the more augitic flows, the ophites, one might expect to find heavier and darker than the porphyrites with more soda, the difference is completely disguised by other factors of primary or secondary variation such as the relative abundance of epidote and copper, or chlorite and calcite and zeolites among minerals, and the amount of primary olivine and iron oxides. The felsites are, of course, distinctly lighter, as well as the sandstones.

§ 16. TABLES OF ANALYSES AND NOTES.

TABLE I.

Lighthouse Point dike. This with the analysis of Tables II-VIII are perhaps of the original Keweenawan magma and are of intrusives showing but slight differentiation, a little accumulation of CaO at center. They were analyzed June 30, 1903, under direction of E. D. Campbell, by E. E. Ware at Ann Arbor. (See Journal of Geology, XII (1904) p. 89). They show very marked resemblance to Nos. 1 and 2, perhaps from a "'Logan sill" of Table II.



	1	1a	3	3a	6	6a	8	8a
SiO_2	46.98	.783	47.67	.794	47.25	.787	47.10	.785
Al_2O_3	17.85	.174	17.55	.171	18.00	.176	17.47	.170
Fe_2O_3	3.13	.020	2.51	.015	2.21	.014	2.06	.016
FeO	10.36	.143	12.69	.176	12.42	.172	12.93	.179
MgO	7.16	.178	5.65	.141	6.35	.159	6.88	.172
CaO	8.47	.151	10.75	.192	11.45	.204	10.27	.183
Na_2O	2.04	.032	2.21	.035	1.96	.030	1.91	.031
K_2O	.60	.006	.65	.006	.66	.006	.59	.005
H_2O-	1.45	.081	.05	.002				
H_2O+	3.02	.167	2.02	.112				
TiO_2								
P_2O_5	.143	.001	.169	.001	.158	.001	.161	.001
CO_2								
S	.097	.002	.183	.004	.086	.002	.111	.003
SO_3								
MnO	.26	.003	.19	.002	.18	.002	.15	.001
Cl	.07	.001	.05	.001	.02	.001	.09	.002
	101.80	1.742	102.422	1.652	100.744	1.554	100.522	1.547
Alkali m. / Silica m.		.048		.053		.047		.0472
Pore space to solid space		.0473		.0012		.0032		.0018
Sp. Gr.[1]		2.83		3.02		3.01		3.02

[1]Taken in gasolene.

1. Contact.
1a. Molecular proportions.
3. .616 mm from margin.
3a. Molecular proportions.
6. 4.115 mm from margin.
6a. Molecular proportions.
8. 7.6 mm from margin.
8a. Molecular proportions.

TABLE II.

Analyses by A. N. Winchell, of Minnesota Keweenawan rocks. Nos. 1 and 2 are of a sill very much like the Lighthouse Point dike, with possibly a slight settling of iron to the bottom, lower northern side. Or is the iron absorbed? These are from his thesis ("Study of the Gabbroid Rocks of Minnesota") of intrusives of probably Keweenawan age, except perhaps No. 3. They are given on page 149 of the French edition of the thesis and also in the American Geologist, Dec., 1900, pp. 373-376 (and p. 262).

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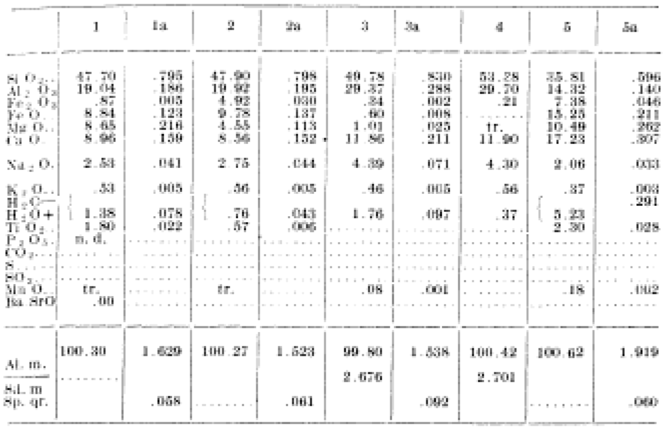
[62] Ex. Doc. No. 5, 31st Congress, 1849.

[63] Geology of Canada, 1866, pp. 142, 143, 147, 154, 160.

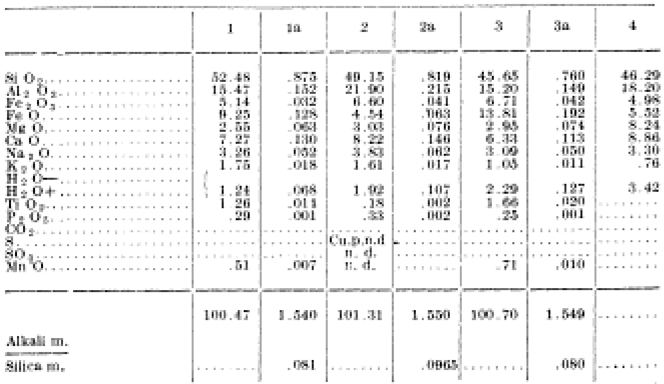


	1	1a	2	2a	3	3a	4	5	5a
SiO_2	47.70	.795	47.90	.798	49.78	.830	53.28	35.81	.596
Al_2O_3	19.04	.186	19.92	.195	29.37	.288	29.70	14.32	.140
Fe_2O_3	.87	.005	4.92	.030	.34	.002	.21	7.38	.046
FeO	8.84	.123	9.78	.137	.60	.008		15.25	.211
MgO	8.65	.216	4.55	.113	1.01	.025	tr.	10.49	.262
CaO	8.96	.159	8.56	.152	11.86	.211	11.90	17.23	.307
Na_2O	2.53	.041	2.75	.044	4.39	.071	4.30	2.06	.033
K_2O	.53	.005	.56	.005	.46	.005	.56	.37	.003
H_2O-									.291
H_2O+	1.38	.078	.76	.043	1.76	.097	.37	5.23	
TiO_2	1.80	.022	.57	.006				2.30	.028
P_2O_5	n. d.								
CO_2									
S									
SO_3									
MnO	tr.		tr.		.08	.001		.18	.002
Ba. SrO	.00								
	100.30	1.629	100.27	1.523	99.80	1.538	100.42	100.62	1.919
Al. m. / Sil. m					2.676		2.701		
Sp. gr.		.058		.061		.092			.060

1. Birch Lake gabbro.
1a. Molecular proportions.
2. Logan sill, Birch Lake, east side.
2a. Molecular proportions.
3. Carlton Peak "plagioclasyte."
3a. Molecular proportions.
4. Plagioclase of 3, (p. 262).
5. Troctolyte near Duluth.
5a. Molecular proportions.

TABLE III.

Duluth gabbro analyses to be compared with the Ashbed magma, Table XII. It has large (3mm.) labradorite phenocrysts, rhocrystals, arranged in flow lines, and has numerous ramifying aplitic red veins. Cf. the Mt. Bohemia rocks. (Tables IX and X). This differs from the Gowganda (Canada) diabase of Bowen in having more iron and less magnesia and lime. The Sudbury norite has as much iron, but a lower alkali: silica ratio.

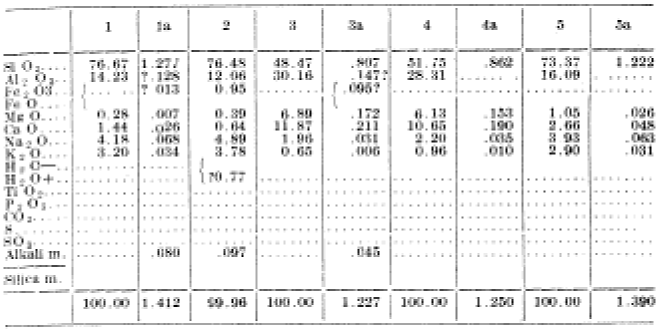


	1	1a	2	2a	3	3a	4
SiO_2	52.48	.875	49.15	.819	45.65	.760	46.29
Al_2O_3	15.47	.152	21.90	.215	15.20	.149	18.20
Fe_2O_3	5.14	.032	6.60	.041	6.71	.042	4.98
FeO	9.25	.128	4.54	.063	13.81	.192	5.32
MgO	2.55	.063	3.03	.076	2.95	.074	8.24
CaO	7.27	.130	8.22	.146	6.33	.113	8.86
Na_2O	3.26	.052	3.83	.062	3.09	.050	3.30
K_2O	1.75	.018	1.61	.017	1.03	.011	.76
H_2O-							
H_2O+	1.24	.068	1.92	.107	2.29	.127	3.42
TiO_2	1.26	.011	.18	.002	1.66	.020	
P_2O_5	.29	.001	.33	.002	.25	.001	
CO_2							
S			Cu.p.n.d				
SO_3			n. d.				
MnO	.51	.007	n. d.		.71	.010	
	100.47	1.540	101.31	1.550	100.70	1.549	
Alkali m. / Silica m.		.081		.0965		.080	

1. From A. N. Winchell, p. 293, No. 1797. No appreciable BaO or SrO. Sp. Gr. 2.81 to 2.84.
1a. Molecular proportions.
2. Same cited from A. Streng, Neues Jahrbuch, 1877, p. 117. MnO and Fl not determined. TiO_2 and P_2O_3 determined separately. Original total 100.80. Chalcopyrite present.
2a. Molecular proportions.
3. Hornblendic variety, of No. 1 richer in iron.
3a. Molecular proportions.
4. Average of analyses of 15515 (top) and 15523 (bottom) of Ashbed diabase, Isle Royale hole 10., 338-415 for comparison. This has more MgO and contained olivine.

TABLE IV.

Bunsen's normal trachytic and normal pyroxenic analyses for comparison. The Keweenawan magma is short in lime compared with the normal pyroxenic, but the ophites approach it closely. This may be the pyroxenic eutectic, while the normal trachyte is not far from Vogt's and Teall's micropegmatite eutectic. Nos. 1 and 3 are Bunsen's ideal normal trachytic and pyroxenic magma while Nos. 4 and 5 are actual analyses of Iceland rock is supposed to be a mixture of the two in varying proportions. These are cited from Neumayr's Erdgeschichte, Vol. I, p. 169. No. 2 is of a spherulite from a porphry, cited by Vogt after Lagorio as Nos. 22a and 31b of his table of quartz feldspar eutectics, p. 174, Part II of "Die Silikatschmelzlösungen."



	1	1a	2	3	3a	4	4a	5	5a
SiO_2	76.67	1.277	76.48	48.47	.807	51.75	.862	73.37	1.222
Al_2O_3	14.23	?.128	12.06	30.16	.147?	28.31		16.09	
Fe_2O_3		?.013	0.95		.095?				
FeO									
MgO	0.28	.007	0.39	6.89	.172	6.13	.153	1.05	.026
CaO	1.44	.026	0.64	11.87	.211	10.65	.190	2.66	.048
Na_2O	4.18	.068	4.89	1.96	.031	2.20	.035	3.93	.063
K_2O	3.20	.034	3.78	0.65	.006	0.96	.010	2.90	.031
H_2O-									
H_2O+			0.77						
TiO_2									
P_2O_5									
CO_2									
S									
SO_3									
Alkali m. / Silica m.		.080	.097		.045				
	100.00	1.412	99.96	100.00	1.227	100.00	1.250	100.00	1.390

1. Normal trachytic.
1a. Molecular proportions.
2. Spherulite (quartz feldspar eutectic) El Pablon, de Itulgache Ecuador.
3. Normal pyroxenic.
3a. Molecular proportions.
4. Reygadalr Foss.
4a. Molecular proportions.
5. Klettaberge.
5a. Molecular proportions.

TABLE V.

Analyses of minerals of Keweenawan basic rocks. Nos. 1 to 3 are from United States Geological Survey Bulletin 418, p. 51. With No. 1 should be compared analyses G, I, J, K of the same bulletin, page 56, of Minnesota gabbro feldspars. With No. 3 should be compared an old analysis by Jackson (Table XIV, No. 3) and analysis 5 by Winchell. It appears that plutonic rocks crystallize under conditions in which less alumina goes into the pyroxene. Cf. r and other analyses in Idding's table of analyses of pyroxene.

	1 H	2 I	3 J	4	5	6
SiO_2		53.30	49.80	45.05	48.34	33.57
Al_2O_3		29.03	2.86	.16	2.90	
Fe_2O_3	50.29	.55	2.48	5.30	4.68	
FeO	39.70	.23	10.82	14.90	14.15	48.74
MgO		.13	15.33	15.15	11.34	17.69
CaO		11.40	16.30	10.72	15.10	
Na_2O		4.87	.51	1.27		
K_2O		.40	.12	.78		
H_2O-		.23	.33	.13	1.98	
H_2O+				4.59		
TiO	8.77	trace	1.29			
P_2O_5		trace	trace			
CO_2						
SrO		trace	none			
Li_2O		none	trace?			
MnO		none	.37	1.58		
BaO		trace	none			
	89.46	100.14	100.41	99.63	98.49	
Sp. Gr.				3.316		

1. Magnetite.
2. Labradorite Ab_{40} An_{60}.
3. Diallage.
4. Pyroxene from Pigeon Point diabase. Am. Geol., Oct., 1900, p. 203. A. N. Winchell.
5. Diallage from Pigeon Point. Am. Geol., Oct., 1900, p. 203. Riggs.
6. Olivine. Am. Geol., Oct., 1900, p. 204. A. N. Winchell.

TABLE VI.

TABLE VI.—*Miscellaneous old analyses from reports of Jackson*[1] *and Foster and Whitney*[2] *showing composition of various secondary minerals.*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
SiO_2	8.91	57.95		52.7	51.000	53.40		49.09	49.06	46.12	37.41	36.99	94.24?	81.10	55.04	$BaSO_4$ 64.1	42.6
Al_2O_3		19.00				22.40		.23	1.28	25.91	24.25	25.49	.47	2.61	22.34	SO_3	31.2
Fe_2O_3	1.98										6.26	6.48	.927	3.91		.64	
FeO		13.06															
MgO	+ CO_2 44.65	1.32						.14					+ CO_2 .07	.25			
CaO	+ CO_2 44.49	.05		23.35	24.944	3.00		46.38	44.87	27.03	21.68	19.90	+ CO_2 .32	.46	10.64	9.07	20.6
Na_2O						8.52				.85	4.88	3.70	++ SO_4 .06	.22			
K_2O				4.95	5.187							.40					
H_2O-		7.81											Org 2.92	8.93			
H_2O+			4.4	16.00	16.00	10.31		2.96	2.96		5.77	7.22	0.73	2.79	11.93	6.97	5.2
TiO_2																	
P_2O_5								Mn O .48									
CO_2								.72	.90							Cu 14.03	
S							Cu 5.26										
SO_3							Ag .005									6.19	
CaF				1.85	1.94												
	100.03	99.19		98.85	99.071	97.63		100.00	100.00	99.91	100.25	100.18					99.6
Sp. Gr.				2.305		2.250 to 2.258						3.18					

[1] House Ex. Doc., No. 5, 31st Congress, 1st Session.

[2] Report on the Geology of the Lake Superior Land District, Pt. III, 1851. Ex. Doc. No. 5. Special session of Senate, March 1851.

1. Limestone Mountain.
2. Native silver gangue, p. 480.
3. Water in prehnite, p. 484.
4. Apophyllite, p. 484.
5. Apophyllite, p. 484.
6. Analcite red, p. 485.
7. Cliff vein, p. 489.
8. Wollastonite, p. 491.
9. Wollastonite, p. 491.
10. Anhydrous prehnite table spar or "Jacksonite," p. 492. See comments later.
11. Chlorastrolite, p. 493. F. & W., p. 97.
12. Chlorastrolite, p. 492. F. & W., p. 97.
13. Soils over Lake Superior sandstone, p. 497.
14. Soils over Trap.
15. Leonhardite (laumontite), p. 513.
16. Mendelhall's mine, p. 513.
17. F. & W. II, p. 88. Hydrous epidote?

Much better analyses, and very important is the work of F. F. Grout, Science, XXXII, (1910) p. 314.

TABLE VII.

Mount Houghton quartz porphyry. From L. L. Hubbard, Geol. Sur. of Mich., Vol. VI, Pt. II. This rock is reported by Jackson (p. 495) as having Sp. Gr. 2.572. The analyses were all by F. P.Burrell.

	1 J	1a	2	2a	3	3a
SiO_2	75.67	1.261	80.05	1.332	69.76	1.162
Al_2O_3	12.43	.121	9.73	.095	13.14	.128
Fe_2O_3	2.27	.014	1.72	.010	1.44	.009
FeO	0.15	.002	0.18	.002	0.66	.009
MgO	0.00	.000	0.00	.000	0.18	.004
CaO	tr.		0.83	.014	0.36	.006
Na_2O	2.01	.032	2.19	.035	2.52	.040
K_2O	6.73	.071	4.43	.047	11.00	.120
H_2O-	0.41	.022	1.03	.057	0.42	.024
H_2O+						
TiO_2						
P_2O_5						
CO_2						
S						
SO_3						
MnO	tr.		tr.			
Alkali m. / Silica m.		.082		.060		.143
	99.67	1.521	100.16	1.589	100.38	1.499

1.[1] Hubbard, p. 28.
1a. Molecular proportions.
2. 17193 A[2] end of Mt. Houghton. Hubbard, p. 42.
2a. Molecular proportions.
3. 16951 Mt. Houghton, south (lower) side.
3a. Molecular proportions.

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[1] 1 does not fuse at 900°, cakes and bleaches, has few small phenocrysts of feldspar.

[2] 17193A shows infiltered quartz.

TABLE VIII.

Transition rocks, porphyrite flows below Mount Houghton quartz porphyry. From L. L. Hubbard, F. P. Burrall, analyst. Perhaps Tables V and VI are both too high in alkalis, like Cook's analyses, as A. N. Winchell suggests (Jour. Geol., XVI (1908), p. 771). They indicate differentiation from right to left along the eutectic valley (Fig. 12) of the same kind as that from the Mount Bohemia gabbro (Table X) to gabbro aplite (Table IX) or syenite.

	1 E	1a	2 G	2a	3	3a
SiO_2	52.83	.880	51.45	.957	59.52	.991
Al_2O_3	16.30	.160	15.75	.154	15.58	.153
Fe_2O_3	9.60	.060	11.12	.069	7.24	.045
FeO	2.48	.035	1.74	.024	1.86	.027
MgO	3.98	.099	1.94	.048	2.11	.052
CaO	2.98	.053	0.12	.002	1.81	.032
Na_2O	6.54	.105	7.84	.126	6.82	.109
K_2O	2.49	.025	3.51	.037	3.48	.036
H_2O-						
H_2O+	2.76	.153	1.23	.067	2.23	.123
TiO_2						
P_2O_5						
CO_2						
S						
SO_3						
Alkali m. / Silica		.148		.170		.147
Sum	99.96	1.567	100.70	1.484		1.572

1. 17033 Hubbard. p. 25, diabase porphyrite, Bed E.[1]
1a. Molecular proportions.
2. 17007 Hubbard, p. 26.[2]
2a. Molecular proportions.
3. 17039[3] p. 26.
3a. Molecular proportions.

---

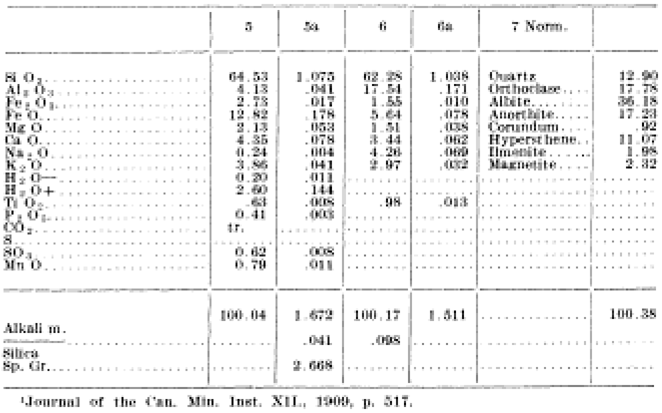
[1] Fusible about 900° C with microlitic ground mass and phenocrysts. Bed E of the Mt. Houghton felsite series.

[2] Feldspar near albite. Ct. gabbro aplites, Bed G. Separated from E by amygdaloid conglomerate, 915N., 1060 W. Sec. 20, T. 58 N., R. 28 W.

[3] Fusible about 900° C to dark brown glassy globule. 1340N., 360 W. Sec. 27, T. 58 N., R 28 W. cf. Praysville porphyry with 59.52 Si, O_2, much more porphyritic; felsite porphyrite, Hubbard, quartzless porphyry, Irving.

TABLE IX.

Intrusive red rock or gabbro aplite of Mount Bohemia. See F. E. Wright, annual report for 1908. Of. Bowen's Gowganda, and the Cobalt (Canada) aplites,[1] the Pigeon Point rocks and other analyses cited by Daly, A. J. S., XX (1905), pp. 193-213. The specific gravity of rock such as Nos. 5 and 6 according to Jackson is 2.631. Nos. 5 and 6 are check analyses from the same rock specimen (not ground powder) by Newell Cook at Albion and L. Kirschbraurn of Ann Arbor. Cook died before his work was finished and some figures are certainly wrong. Much like Bowen's Gowganda granophyre, but I suspect secondary introduction of an iron chlorite.



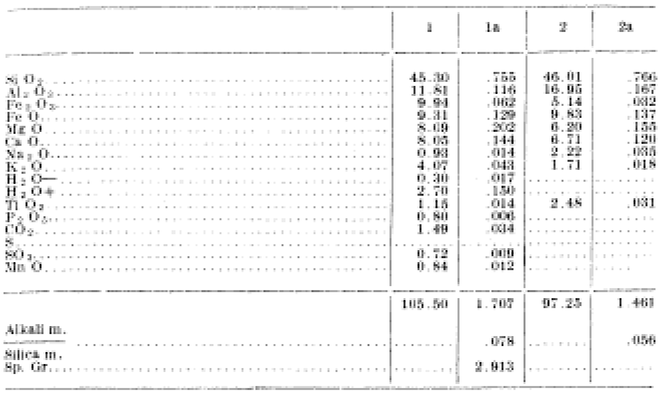
	5	5a	6	6a	7 Norm.	
SiO_2	64.53	1.075	62.28	1.038	Quartz	12.90
Al_2O_3	4.13	.041	17.54	.171	Orthoclase	17.78
Fe_2O_3	2.73	.017	1.55	.010	Albite	36.18
FeO	12.82	.178	5.64	.078	Anorthite	17.23
MgO	2.13	.053	1.51	.038	Corundum	.92
CaO	4.35	.078	3.44	.062	Hypersthene	11.07
Na_2O	0.24	.004	4.26	.069	Ilmenite	1.98
K_2O	3.86	.041	2.97	.032	Magnetite	2.32
H_2O-	0.20	.011				
H_2O+	2.60	.144				
TiO_2	.63	.008	.98	.013		
P_2O_5	0.41	.003				
CO_2	tr.					
S						
SO_3	0.62	.008				
MnO	0.79	.011				
	100.04	1.672	100.17	1.511		100.38
Alkali m. / Silica		.041	.098			
Sp. Gr.		2.668				

[1] Journal of the Can. Min. Inst. XII., 1909, p. 517.

5. Gabbro aplite. Cook loc. cit.
5a. Molecular proportions.
6. Gabbro aplite. K. loc. cit.
6a. Molecular proportions.
7. Norm.

TABLE X.

Mount Bohemia oligoclase gabbro and allied rocks. See annual report for 1908, p. 369.

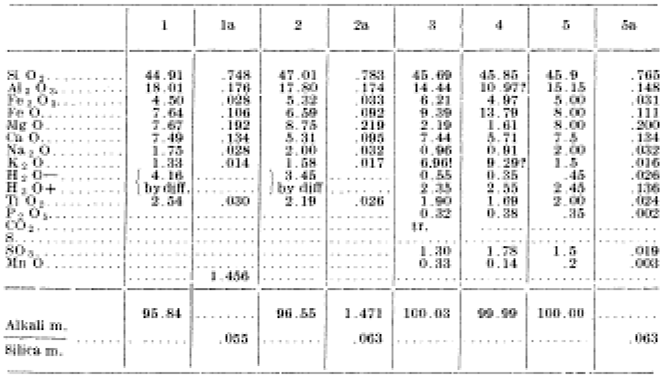


	1	1a	2	2a
SiO_2	45.30	.755	46.01	.766
Al_2O_3	11.81	.116	16.95	.167
Fe_2O_3	9.94	.062	5.14	.032
FeO	9.31	.129	9.83	.137
MgO	8.09	.202	6.20	.155
CaO	8.05	.144	6.71	.120
Na_2O	0.93	.014	2.22	.035
K_2O	4.07	.043	1.71	.018
H_2O-	0.30	.017		
H_2O+	2.70	.150		
TiO_2	1.15	.014	2.48	.031
P_2O_5	0.80	.006		
CO_2	1.49	.034		
S				
SO_3	0.72	.009		
MnO	0.84	.012		
	105.50	1.707	97.25	1.461
Alkali m. / Silica m.		.078		.056
Sp. Gr.		2.913		

1. By N. Cook.
1a. Molecular proportions.
2. By L. Kirschbraum.
2a. Molecular proportions.

TABLE XI.

Mount Bohemia, ophite and contact modification of it. See report for 1908, p. 377.

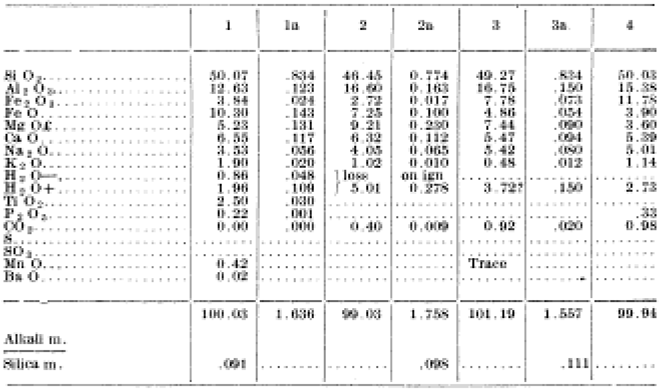


	1	1a	2	2a	3	4	5	5a
SiO_2	44.91	.748	47.01	.783	45.69	45.85	45.9	.765
Al_2O_3	18.01	.176	17.80	.174	14.44	10.97?	15.15	.148
Fe_2O_3	4.50	.028	5.32	.033	6.21	4.97	5.00	.031
FeO	7.64	.106	6.59	.092	9.39	13.79	8.00	.111
MgO	7.67	.192	8.75	.219	2.19	1.61	8.00	.200
CaO	7.49	.134	5.31	.095	7.44	5.71	7.5	.134
Na_2O	1.75	.028	2.00	.032	0.96	0.91	2.00	.032
K_2O	1.33	.014	1.58	.017	6.06!	9.29?	1.5	.016
H_2O-	4.16		3.45		0.55	0.35	.45	.026
H_2O+	by diff.		by diff		2.35	2.55	2.45	.136
TiO_2	2.54	.030	2.19	.026	1.90	1.69	2.00	.024
P_2O_5					0.32	0.38	.35	.002
CO_2					tr.			
S								
SO_3					1.30	1.78	1.5	.019
MnO					0.33	0.14	.2	.003
		1.456						
	95.84		96.55	1.471	100.03	99.99	100.00	
Alkali m. / Silica m.		.055		.063				.063

1. Normal ophite, Sp. 2, F. E. W. 21. This seems low in CaO and SiO_2 for a normal ophite. It may be that iron and magnesia have been introduced in place.
1a. Molecular proportions.
2. Contact phase of same showing alteration. Sp. 2, F. E. W. 37. L. Kirschbraum, analyst.
2a. Molecular proportions.
3. Duplicate of No. 1. Analyzed by N. Cook.
4. Duplicate of No. 2. Analyzed by N. Cook.
5. Most probable analysis, estimated by A. C. L., from all four analyses, since there seems to be no essential difference in composition. Cf. Tables III and XII to XV.
5a. Molecular proportions.

TABLE XII.

Analyses of sodic melaphyres of "Ashbed," Tobin, or melaphyre porphyrite type.



	1	1a	2	2a	3	3a	4
SiO_2	50.07	.834	46.45	0.774	49.27	.834	50.03
Al_2O_3	12.63	.123	16.60	0.163	16.75	.150	15.38
Fe_2O_3	3.84	.024	2.72	0.017	7.78	.073	11.78
FeO	10.30	.143	7.25	0.100	4.86	.054	3.90
MgO	5.23	.131	9.21	0.230	7.44	.090	3.60
CaO	6.55	.117	6.32	0.112	5.47	.094	5.39
Na_2O	3.53	.056	4.05	0.065	5.42	.080	5.01
K_2O	1.90	.020	1.02	0.010	0.48	.012	1.14
H_2O-	0.86	.048	loss	on ign			
H_2O+	1.96	.109	5.01	0.278	3.72?	.150	2.73
TiO_2	2.50	.030					
P_2O_5	0.22	.001					.33
CO_2	0.00	.000	0.40	0.009	0.92	.020	0.98
S							
SO_3							
MnO	0.42				Trace		
BaO	0.02						
	100.03	1.636	99.03	1.758	101.19	1.557	99.94
Alkali m. / Silica m.	.091			.098		.111	

1. Bed 65[1] Eagle River.
1a. Molecular proportions.
2. 15515 Isle Royale, p. 146.[2]
2a. Molecular proportions.
3. 15537 Isle Royale, p. 215.
3a. Molecular proportions.
4. Streng's melaphyr porphyr, N. Jahrbuch, 1877, p. 48; Irving, V, p. 277. Compare the "melaphyre" (ophite) on p. 55.

TABLE XIII.

Melaphyre analyses of uncertain affinities. No. 1 (see Vol. VI, p. 215) is 16 feet from the top of a typical

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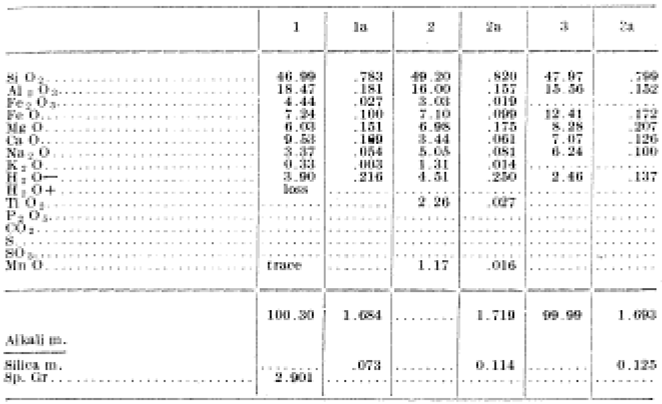
[1] Journal of Geol. XVI, p. 772.

[2] Vol. VI, Part I, pp. 215, 143, 146.

"Ashbed" melaphyre porphyrite. No. 2 is from the middle of a bed (Eagle River 87), the bottom of which is a lime melaphyre, just above the "Mesnard epidote" and below the Pewabic lode. Cited from Pumpelly. Proc. Am. Ac. XIII, p. 285. See also Irving. No. 3 is an old analysis of a rock which being above the Greenstone is more likely to be a sodic melaphyre.



	1	1a	2	2a	3	3a
SiO_2	46.99	.783	49.20	.820	47.97	.799
Al_2O_3	18.47	.181	16.00	.157	15.56	.152
Fe_2O_3	4.44	.027	3.03	.019		
FeO	7.24	.100	7.10	.099	12.41	.172
MgO	6.03	.151	6.98	.175	8.28	.207
CaO	9.53	.170	3.44	.061	7.07	.126
Na_2O	3.37	.054	5.05	.081	6.24	.100
K_2O	0.33	.003	1.31	.014		
H_2O-	3.90	.216	4.51	.250	2.46	.137
H_2O+	loss					
TiO_2			2.26	.027		
P_2O_5						
CO_2						
S						
SO_3						
MnO	trace		1.17	.016		
	100.30	1.684		1.719	99.99	1.693
Alkali m. / Silica m.		.073		0.114		0.125
Sp. Gr.	2.901					

1. 15533[1] Isle Royale, p. 215.
1a. Molecular proportions.
2. Eagle River Bed No. 87.
2a. Molecular proportions.
3. Rock Harbor trap, F. & W., Pt. II, p. 88.
3a. Molecular proportions.

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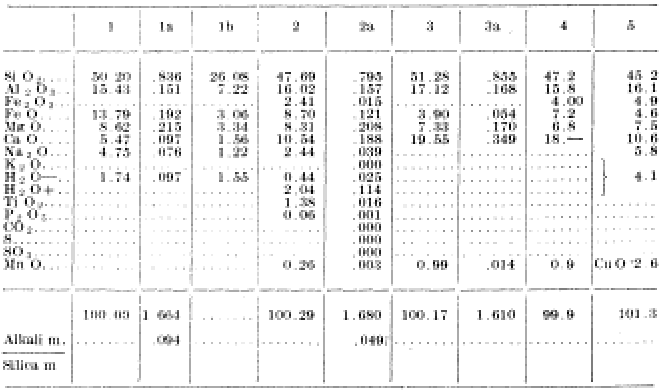
[1] At the page cited will be found another check analysis which is from the same bed, 3 feet farther from the top. This is 16 feet from the top. It is the same bed as 15537 but has more lime.

TABLE XIV.

Analyses of the great flow known as the "Greenstone,"—typically an ophite, at any rate at the base, (see Pls. II and III) though large plagioclase rhyocrystals occasionally occur. None of the analyses are satisfactory. The Foster and Whitney (1) and Jackson analyses (3) are old and incomplete, and the recent U. S. G. S. analysis No. 2 shows no potash. The Jackson analysis (3) is supposed to be of the pyroxene only, but is probably of augite containing feldspar and magnetite. The latter was extracted before analysis. For comparison an ideal analysis of a melaphyre containing .265 per cent of copper is placed beside it.



	1	1a	1b	2	2a	3	3a	4	5
SiO_2	50.20	.836	26.08	47.69	.795	51.28	.855	47.2	45.2
Al_2O_3	15.43	.151	7.22	16.02	.157	17.12	.168	15.8	16.1
Fe_2O_3				2.41	.015			4.00	4.9
FeO	13.79	.192	3.06	8.70	.121	3.90	.054	7.2	4.6
MgO	8.62	.215	3.34	8.31	.208	7.33	.170	6.8	7.5
CaO	5.47	.097	1.56	10.54	.188	19.55	.349	18.—	10.6
Na_2O	4.73	.076	1.22	2.44	.039				5.8
K_2O					.000				
H_2O-	1.74	.097	1.55	0.44	.025				} 4.1
H_2O+				2.04	.114				
TiO_2				1.38	.016				
P_2O_5				0.06	.001				
CO_2					.000				
S					.000				
SO_3					.000				
MnO				0.26	.003	0.99	.014	0.9	CuO 2.6
	100.03	1.664		100.29	1.680	100.17	1.610	99.9	101.3
Alkali m. / Silica m		.094			.040				

1. F. & W. Ft. II, p. 88.
1a. Molecular proportions.
1b. Oxygen of same.2. A. N. Winchell, p. 772.
2a. Molecular proportions.
3. Pyroxene from same.
3. Pyroxene Jackson (p. 494) gives this analysis of a "pyroxene" associated with feldspar, magnetite and ilmenite on a hill in Sections 12 and 13, T. 58 N. R. 28 W. This is almost certainly from the Greenstone Range. The H. was 5.5, Hp. gr. 3.478. It may have been one of the ophitic augite patches as that would account for the alumina and alkalis, The magnetic part he separated. If we add enough FeO Fe_2O_3 to make the amount of iron generally found in the Greenstone,—say 8.3% $FeOFe_2O_3$—the analysis will be closely that of the Greenstone except that the alkalis were not tested and the lime is extra high. Assignment of the bases to the silica indicates strongly that some alkalis were present, perhaps included with the lime in this old analysis. Compare, however, Doelter's analysis (Hintze CCCXI) of brown augite from, a Cape Verde feldspar basalt. It may represent the eutectic, Fig. 13.
3a. Molecular proportions.
4. No. 3 with 8.3 per cent magnetite added.
5. Ideal melaphyre used in showing change to chlorite and copper repeated for comparison from p. 86.

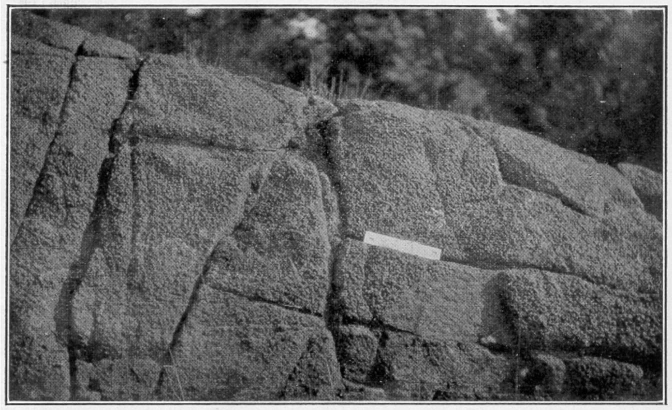
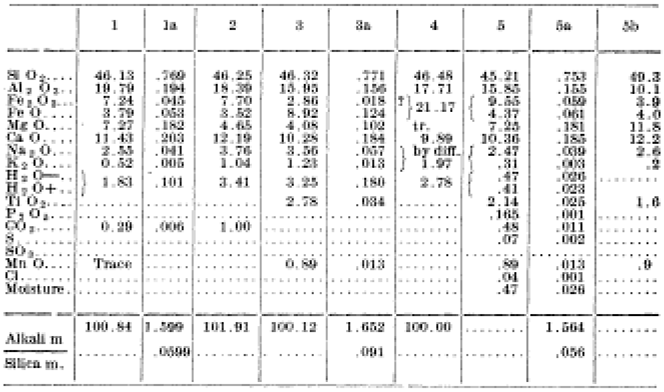


Plate III. (A.) Weathered surface of the ophite taken at about the same time as Plate II by W. J. Penhallegon.

Plate III. (B.) Weathered surface of amygdaloid conglomerate after Figure 2, Part 2 of Volume VI.

TABLE XV.

Analyses from different analysts of lime melaphyre (ophites), different beds, but all of the commonest type of Keweenawan flow. The percentages of silica agree closely; the alumina agrees (allowing for the fact that the titanium oxide was not separated in two cases). The relative proportions of ferrous and ferric iron vary greatly. The MgO checks closely in the two most recent analyses. The lime is characteristic and always about 10 per cent and never 12 per cent. The soda and potash agree very closely in the two better analyses 1 and 5, and the titanium oxide is high.



	1	1a	2	3	3a	4	5	5a	5b
SiO_2....	46.13	.769	46.25	46.32	.771	46.48	45.21	.753	49.3
Al_2O_3...	19.79	.194	18.39	15.95	.156	17.71	15.85	.155	10.1
Fe_2O_3...	7.24	.045	7.70	2.86	.018	?} 21.17	9.55	.059	3.9
FeO....	3.79	.053	3.52	8.92	.124		4.37	.061	4.0
MgO....	7.27	.182	4.65	4.08	.102	tr.	7.25	.181	11.8
CaO....	11.43	.203	12.19	10.28	.184	9.89	10.36	.185	12.2
Na_2O...	2.55	.041	3.76	3.56	.057	} by diff. 1.97	2.47	.039	2.6
K_2O....	0.52	.005	1.04	1.23	.013		.31	.003	.2
H_2O—..	} 1.83	.101	3.41	3.25	.180	2.78	.47	.026	....
H_2O+..							.41	.023	
TiO_2...	....	....	....	2.78	.034	....	2.14	.025	1.6
P_2O_5...	....	....	....	....	....	....	.165	.001	....
CO_2....	0.29	.006	1.00	....	....	....	.48	.011	....
S........	....	....	....	....	....	....	.07	.002	....
SO_3....	....	....	....	....	....	....	....	....	....
MnO....	Trace	....	....	0.89	.013	....	.89	.013	.9
Cl.......	....	....	....	....	....	....	.04	.001	....
Moisture.	....	....	....	....	....	....	.47	.026	....
	100.84	1.599	101.91	100.12	1.652	100.00	....	1.564	....
Alkali m / Silica m.	....	.0599	....	....	.091	....	....	.056	....

1. Ophitic streak 9 feet from base of same (77-foot) bed as 15515 and 15519, Eagle River 3943, Sp. 15523; Sp. Gr. 2.877. See average composition of bed on Table III.

1a. Molecular proportions.

2. Same bed as No. 1 but 41 feet from base, i. e., near center, the extra lime evidently due to extra calcite. Sp. 15519.
3. Bed 87 just above Greenstone, base of bed more calcareous. Woodward for Pumpelly.

3a. Molecular proportions.

4. Canada report, 1866, p. 157 and seq., very incomplete but suggestively like the others; really, however, from the "Ashbed" group, a "green earth" from the Pewabic lode.
5. St. Mary's Mineral Land Co., Challenge exploration, Hole No. 5 drill core described below.

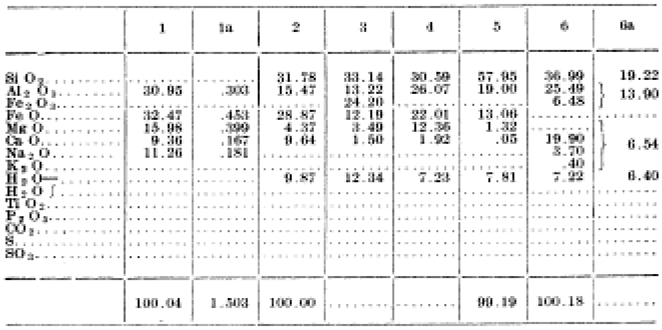
5a. Molecular proportions.

5b. Molecules reduced to per cent after Osann.

The table might be extended by analyses of Table XI, 15533 of Table XIII and the Sank Rapids melaphyre of Streng (Neues Jahrbuch, 1877). Cf. also Table I, Nos. 3 to 8 and Grout's analyses in Science (loc. cit.) and Journal of Geol. 1910, p. 633 and the analyses in Monograph 52, p. 583, especially 1.

TABLE XVI.

Analyses of chloritic materials. See also analysis 4, of previous table.



	1	1a	2	3	4	5	6	6a
SiO_2..........	....	....	31.78	33.14	30.59	57.95	36.99	19.22
Al_2O_3.........	30.95	.303	15.47	13.22	26.07	19.00	25.49	} 13.90
Fe_2O_3.........	....	....	....	24.20	....	....	6.48	
FeO...........	32.47	.453	28.87	12.19	22.01	13.06	....	....
MgO...........	15.98	.399	4.37	3.49	12.36	1.32	....	} 6.54
CaO...........	9.36	.167	9.64	1.50	1.92	.05	19.90	
Na_2O..........	11.26	.181	....	....	....	....	3.70	
K_2O...........	....	....	....	....	....	....	.40	
H_2O—	....	....	9.87	12.34	7.23	7.81	7.22	6.40
H_2O }	....	....	....	....	....	....	....	....
TiO_2..........	....	....	....	....	....	....	....	....
P_2O_5..........	....	....	....	....	....	....	....	....
CO_2...........	....	....	....	....	....	....	....	....
S..............	....	....	....	....	....	....	....	....
SO_3...........	....	....	....	....	....	....	....	....
	100.04	1.503	100.00	....	....	99.19	100.18	....

1. Soluble part (21.17%) of Greenstone after long digestion in HCl of Sp. Gr. 1.13, not pure chlorite. From Foster and Whitney.

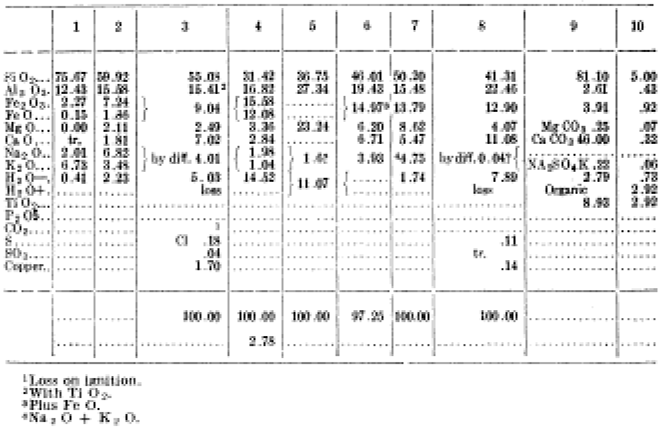
1a. Molecular proportions.

2. Chloritic mineral computed from partial analysis, Quincy wall rock. Soluble part 43.36% of hanging of Quincy vein "mineral chlorite." "Smooth pellet" of green substance which does not cling to Avails. See Macfarlane's "Geologie du Canada, 1866, p. 155.
3. Chlorite from amygdaloid of Pewabic lode, Quincy mine foot. Macfarlane, p. 158. Density of amygdaloid 2.78, composition estimated 62% labradorite, 38% chlorite.
4. "Strigovite" from amygdule in Minnesota. Geol. Sur. 23rd report, p. 194.
5. Analysis of chloritic material with native silver, probably mixed with quartz from Jackson.
6. Chlorastrolite. A number of other analyses will be found in Dana's Mineralogy agreeing essentially with this. This may (Fig. 14) be considered as a mixture of prehnite 43.69 SiO_2, 24.78 Al_2O_3, 27.16 CaO, 4.37 H_2O with about 50% of a chlorite like analyses 3 or 4; the amounts of silica, alumina, lime and water checking closely.

6a. Oxygen ratio.

TABLE XVII.

Analyses grouped to illustrate derivation of sedimentary from igneous rocks.



	1	2	3	4	5	6	7	8	9	10
SiO_2...	75.67	59.92	55.08	31.42	36.75	46.01	50.30	41.31	81.10	5.00
Al_2O_3.	12.43	15.58	15.41[2]	16.82	27.34	19.43	15.48	22.46	2.61	.43
Fe_2O_3.	2.27	7.24	} 9.04	15.58	....	} 14.97[3]	13.79	12.90	3.91	.92
FeO...	0.15	1.46		12.08	....					
MgO...	0.00	2.11	2.49	3.36	23.24	6.20	8.62	4.07	$MgCO_3$ .35	.07
CaO...	tr.	1.81	7.02	2.84	....	6.71	5.47	11.06	$CaCO_3$ 40.00	.32
Na_2O..	2.01	6.82	} by diff. 4.01	1.98	} 1.42	3.93	[4]4.75	by diff. 0.04?	....	....
K_2O...	6.72	3.48		1.04					NA_2SO_4K .22	.06
H_2O—.	0.41	2.23	5.03	14.52	} 11.07	....	1.74	7.59	2.79	.73
H_2O+.	....	....	loss	....		....	....	loss	Organic	2.92
TiO_2...	....	....	....	....	....	....	....	....	8.93	2.92
P_2O_5..	....	....	....	....	....	....	....	....	....	....
CO_2...	....	....	[1]	....	....	....	....	....	....	....
S.......	....	....	Cl .18	....	....	....	....	.11	....	....
SO_3...	....	....	.04	....	....	....	....	tr.	....	....
Copper.	....	....	1.70	....	....	....	....	.14	....	....
	....	....	100.00	100.00	100.00	97.25	100.00	100.00	....	....
	....	....	....	2.78	....	....	....	....	....	....

[1] Loss on ignition.
[2] With TiO_2.
[3] Plus FeO.
[4] $Na_2O + K_2O$.

1. Fresh felsite from Table VII.
2. Diabase porphyrite from Table VIII (original rock of No. 4).
3. Calumet conglomerate slime from J. B. Cooper, Supt. C. and H. Smelter.

4. Calumet conglomerate altered boulder, Wilson. See § 10. ALTERATION OF CALUMET AND HECLA BOULDER..
5. Calumet conglomerate altered boulder, Heath. See § 10. ALTERATION OF CALUMET AND HECLA BOULDER.
6. Mt. Bohemia gabbro from Table X,
7. The "Greenstone" or largest ophite (Table XIV) I cite old imperfect analysis because better comparable.
8. Osceola amygdaloid slime, from J. B. Cooper, Supt. C. and H. Smelter.
9. Keweenaw soil, from Jackson's report, loc. cit.
10. Lake Superior (Upper Cambrian) sandstone soil. The drop in silica and alkalies and rise in alumina are clear.

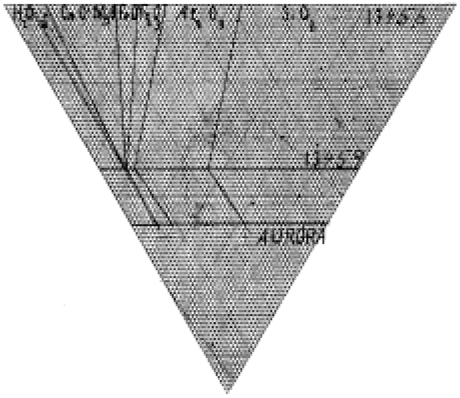


Figure 15. Diagram illustrates abstraction of material attendant upon the alteration of diabase to kaolin.

TABLE XVIII.

Analyses illustrating kaolinitic alteration.

	1	1a	2	2a	3	4	5
SiO_2	47.99	.83 .800	58.22	.970	47.90	46.85	41.60
Al_2O_3	16.57	.58 .162	28.66	.281	15.60	22.62	37.20
Fe_2O_3	6.01	2.35 .038	2.56	.016	3.69	5.12	3.21
FeO	5.13	23.49 .071	0.22	.003	8.41	1.58	.30
MgO	6.01	.150			8.11	2.01	.02
CaO	9.36	.55 .167	0.17	.003	9.99	1.25	.23
Na_2O	2.00	.032			2.05	.80	.07
K_2O	1.39	.015			0.23	2.66	
H_2O-					.15	3.12	.29
H_2O+	2.64	.25 .148	10.50	.583	2.34	8.25	13.54
TiO_2	2.71	.034			0.82	1.12	3.79
P_2O_5					.13	.16	.14
CO_2					.38	1.89	.38
S					Cr_2O_3 tr		
SO_3					NiO .10	.08	
					BaO .05	.10	
MnO	tr.				.17	2.54	.08
					100.12	100.15	

1. Mich. Geol. Sur., 1892, p. 141. Analysis by F. F. Sharpless. See also p. 185 and Vol. VI, p. 247-250 and 265. Lake shaft, Cleveland mine. Relatively fresh. 13456.
1a. Molecular proportions. The figures above each molecular proportion indicate the ratio of the ingredient in the fresh and unaltered rock respectively.
2. Same changed to kaolinite.
2a. Molecular proportions.
3. Diabases, Gogebic Range, dike, S. E. Cor. Ces. 13, T. 47 N., R. 46 W. See also Van Hise, Mon. XIX, p. 357, LII, p. 246, Bull. 168, p. 73; Bull. 419, p. 50.
4. Same altered, the pyroxene to hornblende, and hornblende and feldspar to biotite. P. R. C. 1000. Feldspar is also analyzed with .41 K_2O, 3.48 Na_2O, 11.70 CaO.
5. Dike from Aurora mine altered to kaolinite. U. S. G. S. Bull. 168, p. 73. See also Van Hise, Mon. XIX, Part I, p. 265; U. S. G. S., Bull, 419, p. 50, entirely comparable to No. 2. Cf. analyses of water from that mine, taken just over this dike given in Ch. VII § 4.

TABLE XIX.

Keweenawan sedimentaries and the Lake Superior sandstone.

	1	2	3	4	5	6	7
SiO_2	55.09	63.09	69.78	75.19	87.02	82.60	77.18
Al_2O_3	15.41	18.58	15.43	10.78	7.17	8.32	9.69
Fe_2O_3	9.04	2.17	7.93	4.01	3.91	0.28	3.20
FeO		2.73		1.05			
MgO	2.49	2.67	1.17	0.95	.06	0.18	1.48
CaO	7.02	1.11	.49	2.36	.11	0.55	0.26
Na_2O	4.01 diff	4.54	2.42	1.93	.22		0.18
K_2O		.54	2.64	0.93	1.43	6.49	4.67
H_2O-	5.03 loss inc. CO_2	2.69	2.61		tr.	0.99	2.90
H_2O+							
TiO_2		.99					
P_2O_5	Cl. .18	.12				0.05	0.21
CO_2							
S	.04	tr.					
Cu	1.70	.008				SO_3 0.31	0.23
Pd		tr. +					
MnO_2		.22				0.13	
			100.36		99.92		
Sp. Gr.			2.43!?		2.18		

1. Calumet conglomerate slime undoubtedly is low in felsitic material and one should add to it a proportion of material like the analyses of Table VII. The analysis is nearly that of a mixture of felsite and amygdaloid slime.
2. Nonesuch formation. White Pine drill hole 34 at 500 feet, black chloritlc slate. Analyzed by C. R. Guysander, Cochrane Chemical Co. Appears to be a black sand concentration largely of debris as compared with 3 and 4, as shown by the increase in amount of soda and magnesia, and ferrous iron, and alumina.

   In 3 and 4 iron is probably oxide and hydrate, and lime carbonate. The characteristic difference as against Lake Superior sandstone is the lower potash, but there is a gradual transition.
3. Coarse red sandstone. Leighy's on Bad River, Ashland Co. Analysis by E. J. Sweet, Wisc. Geol. Sur., III, p. 350. The Sp. Gr. given evidently includes the pores.
4. Point Houghton, Isle Royale red sandstone. Isle Royale Minn. Geol. Sur., Bull. 8, p. XXXIII, G. g. No. 555. See also 10th annual report, 1882, pp. 49-54. This was marketed as Isle Royale brownstone by Burchan & Co., 117 Griswold St., Detroit.

5.	*Marquette brownstone, Sharpless in Wadsworth's report, Mich. Geol. Sur., 1893, p. 157.*
6. Lake Superior Sandstone	*Portage Entry redstone, Sharpless in Wadsworth's report, Mich. Geol. Sur., 1893, p. 157.*
7.	*Basswood Island, Apostle Island. Sweet Wisc. Geol. Sur., III, p. 350.*

CHAPTER III. MICROSCOPIC PETROGRAPHY.

§ 1. HISTORICAL INTRODUCTION.

The mineralogical microscopic petrography of the fresh unaltered Keweenawan rocks is not very complicated. Here again as in the chemical work the most thorough and excellent recent work has been done by Alexander N. Winchell.[1] But notes will be found in the annual reports by F. E. Wright, Gordon and myself. The older work of Wadsworth, Irving[2] and Pumpelly[3] was excellent for Its time and a number of other papers are cited by those authors, and need not be repeated here.[4] Suffice it to say that almost all the work on this subject is found either in the United States, Wisconsin, Minnesota or Canadian Survey reports and that all these Surveys have done work upon Michigan rocks as well as upon the rocks of their own region since the development of the copper industry has been much greater in Michigan, thus affording better chance to study the rocks. My own work on the petrography is largely incorporated in Vol. VI of these reports and since then I have done comparatively little microscopic work that brought out new mineralogical facts. Perhaps the most interesting is the recognition of a peculiar aegrite or acmite in a Keweenawan dike rock cutting the Virginia slates.[5] I would call attention to the early use in Volume VI of Becke and Exner's method of determining differences of refraction (p. 154). One may grasp a popular idea of this method and its later improvements if one will hold a bottleful of water close to a window at one side. Then one will see that the light coining in from the window suffers total reflection on the further side of the bottle from the window. Thus any object obliquely illuminated lying in a medium of less refraction (if the border between the two media is anything like the bottle) will have a similar effect,—a bright border on the side opposite to that from which the source of light is. It must be remembered that the field of view is reversed in the microscope so that the effect is apparently reversed. If the index of refraction of a grain immersed in a fluid is clery close to that of the fluid, it may very easily be seen that for certain wave lengths the index of refraction will be greater than that of the fluid, for others less. Then those rays for which the index is greater will have, just like the bottle, a bright border on the side furthest from the source of light which will, however, be distinctly colored. If, instead of being a bottle, it is a bubble which is surrounded by a fluid of higher index the bright spot will be on the side nearest to the source of light, as may also be easily seen by shaking up the fluid in the bottle and watching the effect on the bubbles, and if the fluid is so near the index of refraction of the immersed grain for some wave lengths above and others below we shall have the bright border on the far side for one color and on the near side for another. Practically the grains will be bluish on one side and yellowish on the other. This method has been worked up very elaborately lately by Schroeder Van der Kolk and F. E. Wright of Washington and a series of fluids with different indices put up so that by a little study one can tell whether a grain is above or below in index that of the various fluids and thus determine its character. Not only that, but if, as is generally true, the polarizer of the petrographic microscope allows the light to go through only in one direction,—by revolving the grain we get the index for different directions much more closely than heretofore.

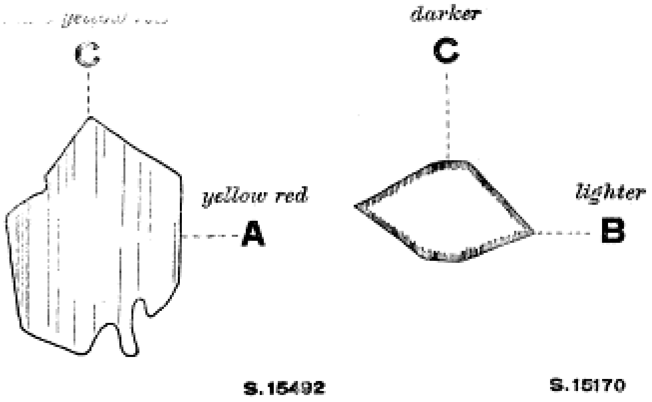


Figure 16. Illustrates optical properties of altered olivine. Reproduced from Vol. VI, Part 1, Figure 23.

It has seemed, on the whole, best to place the detailed microscopic descriptions in connection with the various cross-sections, from which the specimens have come. We may also refer to the paper by F. E. Wright in the report for 1908, papers by N. H. and A. N. Winchell above cited, etc. The fullest set of (1000) thin (Sections were made from the Isle Royale drill holes. These sections cover the range of textures so perfectly that it has seemed needful to cut only occasional microscopic sections since, a list of which will be found elsewhere. Beside those cut for the Survey I have had cut personally from forty to one hundred of the Cape Mamainse and other Keweenawan, but not Michigan, rocks.

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[1] Etude mineralogique et petrographique des roches gabbroiques de l'Etat de Minnesota, Etats Unis, et plus specialement des anorthosites. 1909. Mineralogical and Petrographic study of the Gabbroid Rocks of Minnesota; and more particularly of the Plagioclasytes, American Geologist, XXVI, 1900.

[2] Copper Bearing Rocks of Lake Superior, Monograph V, U. S. G. S.

§ 2. MINERALS.

Olivine is the oldest of the essential minerals. When it occurs it is most conspicuous near the margin of dikes and tops of flows. It tends to be corroded in which case augite seems to grow at the expense of it. When there is less lime there is more olivine developed. Its alteration (Isle Royale Report, Figs. 23-29) may be to serpentine. Occasionally it is to talc or brucite. Another line of alteration is that of oxidation in which it turns red (Fig. 16) and passes into a series of ambiguous minerals variously known. The iddingsite of Lawson is similar. Rubellan was a name much used by Rominger and Pnmpelly.[6] The mineral described as bowlingite by Winchell seems to be the same substance or at least; very similar. Biotite, perhaps, and hematite unquestionably also occur.

Augite. As I have said in Volume VI, when the augite is scarce it is idiomorphic, lighter in color and appears to be diopside (sahlite). When more abundant it is poikilitic or ophitic as explained and illustrated below. Winchell has described the augite of Pigeon Point very thoroughly and has given an analysis. (C.f. Chapter II, Tables 5 and 14).

It will be noticed that this analysis is not unlike the analysis of most of the diabases and ophites, differing mainly in having more ferrous iron magnesia and titanium. Winchell calls it pigeonite and writes me that it probably also occurs elsewhere in the Keweenawan rocks.

There is very often a tendency toward idiomorphism even in the ophitic texture. This is sometimes entirely imperceptible in thin sections but on studying the flashes from a specimen showing the luster mottling it will often appear that they are elongate parallel to the vertical axis, or bounded by straight lines which have a definite crystallographic meaning. A slight tinge of violet such as is given by titanium is especially common in ophitic augite. The more markedly titaniferous kinds are rare. Decomposition of augite to chlorite is very abundant but I do not think that all the chlorite replaces augite. Some of it seems to occupy original interstices left vacant or filled only with hot water in the crystallization and shrinking of the augite. Epidote also replaces the augite. Hornblende seems to replace augite only in a very few cases and then mostly when an augitic rock has been metamorphosed by injection with some later intrusive.

There is a zone of hornblende developed from the augite around the Mt. Bohemia gabbro as described by Wright on page 375 of the annual report for 1908. (See also Vol. VI, p. 73.)

Feldspars. I have determined feldspars mostly by the method illustrated on Plate V, Volume VI.[7] Almost always one can find sections cut nearly parallel to the clinopinacoid (recognizable by the sharp lines between the albite lamellae) in which there are at least three different directions of extinction and in such cases either from the curves given in Plate V or from those given in Rosenbusch's "Microscopic Physiography,"[8] or Winchell's "Optical Mineralogy" one can tell pretty nearly what the feldspar must be. I owe to F. E. Wright a set of fluids ranging in refraction from that of augite 1.523 to that of anorthite 1.58 by which also the feldspars can be readily determined in a powder.

Quartz and other forms of silica. Very recently quartz has assumed a much greater interest owing to the fact that it has been found that silica crystallizes in three different forms according to the temperature and these limits are pretty carefully determined. I regret that most of the work was done before the methods determined by Mügge and Wright and Larsen were developed so that I am not able to speak as definitely as I should like about this matter. Tridymite has never been found, but in such old rocks it probably would in any case have been changed to forms more stable at low temperatures by this time. There is, however, little question from the form of the quartz in the quartz porphyries that much of that crystallized between 550 degrees and 800 degrees O. The vein quartz like that described by Undo[9] was formed at lower temperatures.

Opaque Minerals. Magnetite is generally in octahedral grains though very often they are more skeletal-like in their form. It not infrequently occurs when, it seems to be the product of oxydation accompanying hydration. In the typical melaphyres or cross-grain it is often clear that it formed after the feldspar as it is indented by the feldspar laths. If I were going to do my work over again and make a large number of thin sections I think I should pay especial attention to the abundance and form of the iron oxides. It seems also to form as a by-product of the alteration of olivine to augite and thus occurs in the rock forms crowded into the interstices between the patches of augite. In the Isle Royale report (p. 162) by a slip of the pen I wrote "olivine" patches.

Something that may be taken for magnetite is widely distributed as a fine dust, but it is by no means certain whether it is or not. In one dike north of Bessemer there seems to be both graphite and magnetite present under conditions which make it extremely hard to tell just how much is magnetite and how much graphite in thin sections. I think the graphite is more feathery. In alteration spots and around amygdule cavities it gathers into club-shaped and branching aggregates and sometimes iron oxide outlines brecciated and fragmental and perlitic textures. Distinct crystalline and red hematite is more rare. Ilmenits or titaniferous iron ore

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[3] Lithology of the Keweenawan or Copper Bearing System. Wis. Geological Survey, Vol. III.

[4] Bibliographies seem unnecessary in view of those issued by the U. S. G. S. as bulletins, but I would call attention to Tight and Herrick's work on Michipicoten. Bull. Denison University. Some additional titles are given in an appendix.

Rominger's section descriptions are given in Vol. V., Pt. I, F. E. Wright's work is in. the report for 1908 of Mich. Geol. Survey.

G. Lincio's paper, Neues Jahrbuch für Min. (XVIII) p. 155, I do not find listed.

[5] Report for 1908, p. 304.

occurs and occasionally its white alteration product known as leucoxene. This seems to occur also in some of the epidotic replacements. Ferritic discoloration gives to the sedimentary beds and to the red amygdaloids their characteristic color.

Green decomposition products or viridite. There is an old name, —viridite,—which is a convenient one for the secondary hydrous magnesian silicates of green color, which probably form an isomorphic series. Their optical properties have been fairly fully discussed in Volume VI, Part I, and also by Winchell in his recent text-book on optical mineralogy. It is probable that ferrous iron is a very important constituent of the group. I can readily distinguish the three following varieties:—(1) Serpentine with its usual properties after olivine, (2) delessite or iron chlorite, probably including such varieties as strigovite, etc. This is more birefringent and more fibrous than (3) the ordinary chlorite. Chlorastrolite, as Hawes says, seems to be a compound product of some alteration which is changing to chlorite the hard amygdules of some other substance, often prehnite. Chlorastrolite has been found recently not only in Isle Royale on the patch indicated in my map of Isle Royale, Pl. I, where it was originally found but in a number of beds on Keweenaw Point. For instance, a good deal was developed in the workings of the Keweenawan Copper Company at the Medora shaft, and it has been recognized by Dr. Hubbard at a number of places on Keweenaw Point. It there occurs in an amygdaloid which is reddened and decomposed, in which the decomposition has gone on faster in the body of the rather coarse amygdaloid than in the amygdules. Under such conditions a change takes place around the borders of the prehnitic amygdules. In view of what we know of the concentric character of amygdule filling, however, it is not always easy to prove that the green chatoyant effect of chlorastrolite is not due to an original rind of chlorite. Again, the centers of the amygdules are sometimes occupied by quartz and I should not wish to say that thomsonite or some other zeolites may not sometimes be the original mineral rather than prehnite. A. N. Winchell* (p. 410) seems to be inclined to think that some "chlorastrolite" of northern Minnesota should be grouped under thomsonite. In any case the chemical reaction seems very much that which we have found to be characteristic of decomposition, for instance, of the Calumet and Hecla boulders where magnesia and iron replaces lime and perhaps soda.

Laumontite is well characterized and its optical properties are fully given by Winchell. It customarily has a reddish tinge and tends to disintegrate to a sawdust-like powder. This ready loss of water probably accounts for considerable variation in its optical characteristics. Its index of refraction, however, is always low and it seems to be, on the whole, more of a mineral to occur in cracks in joint-planes and the decomposition of the rock directly from them.

Thomsonite. In casual examination of drill cores I may have often confused this with a pink fibrous radiating prehnite which also occurs. Mesolite and other zeolites may have been overlooked.

Wollastonite? In the Amherst mineral collection there is a piece of considerable size labelled "table spar, Isle Royale" in Jackson's own handwriting as Professor Emerson informs me, and of this he was kind enough to give me a small piece. I think there can be no doubt that this is the same mineral as that referred to in his report on page 491 or at least the Isle Royale variety of it.

The Amherst specimen is perfectly white, hardness 6 and more, color snow white, as though it had already been heated. The Sp. Gr. I found to be less than 2.7, the index of refraction (by immersion in a series of fluids) is about 1.56, the bi-refraction is .022 and more, judging by the polarization colors (assuming thickness not greater than breadth.) It seems, as seen through the microscope under crossed nicols, that the granular aggregate is not entirely homogeneous but largely in irregular patches and as Winchell says for Jacksonite, the elongation seems to be positive, the extinction angle practically zero. It does not, therefore, precisely agree with any other mineral but on the other hand there seems to be some confusion between this “table spar" or "Wollastonite" and Jacksonite.

This Isle Royale table spar agrees with the Wollaistonite of the Cliff mine except in shade of color, that being light flesh red. With a hardness so much *above* that of Wollastonite and its refraction *less* it can not be that mineral. Since the microscope shows that it is an aggregate I do not care to give it a new name. Dana says that the anhydrous prehnite or Jacksonite is only calcined prehnite (conceivably by some severe forest fire?). Perhaps the table spar is produced in the same way. If the analysis is right (Table VI) I know of no known mineral that it is likely to be. The following is a letter from Prof. Ford.

New Haven, Conn., Oct. 28th, 1910.

My Dear Prof. Lane:

We have four specimens in the Brush Collection of so-called table spar from Isle Royale. One specimen has a Smithsonian label with it which! reads "Jacksonite" and has also a label attached to the specimen which says, "Jacksonite and Compact Table Spar." Then there are three other specimens identical in character which Prof. Brush has labeled pectolite. What the material really is I won't venture to say but it is unquestionably not Wollastonite. I have asked Prof. Brush about the specimens and some of them at least came from Whitney and are the original material.

Most sincerely yours,
WM. E. FORD.

Calcite is abundant in large crystals and amygdules, in replacement and in veins. Bands of pressure twinning are not uncommon but may, of course, be due to the pressure in the process of preparing thin sections. It is very abundant as a cement in the conglomerates but it has been suggested that it is more common near the surface than in great depths. Rocks charged with calcite are frequently poikilitic, large patches disseminated from the rock extinguishing together and having common cleavage. This produces a luster mottling which must not be confused with that due to augite.

Epidote. This mineral is one of the most common secondary minerals. The ferriferous canary yellow variety, not the zoisitic variety, is best developed. It occurs in veins in the fragments and cements of the conglomerates and in amygdules, and is very common and the association with quartz is rather characteristic. It is often in sharp crystals.

Datolite occurs mainly in rocks which are quite highly decomposed. It is one of the later minerals after copper, more commonly after quartz and epidote. I had a section cut (sp. 20359) of some datolite from the Winona mine which is studded with minute crystals of copper and separated from the chloritic country rock to a large extent by a thin film of copper.

Nodules of porcelain-like datolite from the Franklin Junior Mine similarly show the copper more abundant near the margin.

Copper. When in microscopic size, copper seems to occur in minute cubes or octahedra although the hextetrahedral and other forms have been noticed in the large crystals described by E. S. Dana and frequently found in mining.

Mica. The micaceous minerals, shading into chlorite and sericite or talc on the one hand and micaceous iron oxide on the other, which occur in the decomposition of olivine and have been variously called iddingsite, rubellan, and bowlingite, which is defined by Winchell as a ferriferous antigorite, are fully described by A. N. Winchell. Winchell says that goethite,—the hydrated iron oxide which always occurs after olivine,—has a higher refringence, while the iddingsite like all the serpentine group has a much lower refringence than the olivine. Unfortunately, I have not kept track of this throughout my work but my impression is that most of the brown specks which have been called rubellan in microscopic work by Pumpelly, Marvine, and Rominger and which I have heretofore called iddingsite, have a relatively low refraction and should be classed as bowlingite. It is quite clear in comparing Winchell's description (p. 360) with my description (p. 155)[10] that we are dealing with very similar substances, except that in his figure and in mine different pinacoids seem to have been present.

Clay and kaolin. The clay of the fluccans has almost no action upon polarized light and is a very finely divided aggregate.

Apatite seems to be a mineral which crystallized early in sharp needles, or possibly slowly throughout the process of crystallization but has a strong tendency to segregation. Possibly the little needles simply floated in the residual magmas. It also seems to occur abundantly in the interstices in the last crystallizations from the mother liquor in needles shooting across the cavities. It suggests the presence of chlorine in these waters (See Sp. 17530, a doleritic melaphyre, 75 paces N., 1050 W. of the S. E. 1/4 of section 33, T. 57 N., E, 32 W., below the Kearsarge amygdaloid in the Allouez gap),

Fluorite has been noticed but very rarely (Isle Royale, Mamainse) and then always in association with the porphyries or salic rocks. The very low refraction and the well-marked cleavage are characteristic and there is a tendency to irregular blue pigmentation.

Sulphides are, on the whole, extremely rare. In fact, I think I have seen disseminated pyrite only when I suspected or was sure of contact action. Chalcopyrite is noticeable, for example, along some of the lines of contact of apparently intrusive felsite at Mamainse, and also near the Mt. Bohemia intrusion in the Calumet and Hecla Mendota section. I have not identified the more basic sulphides and arsenides which offer a splendid field for metallographic work.

§ 3. TEXTURES.

The texture of a rock is defined by Iddings as "the appearance which is derived from the mineral compounds and from the ground mass of dense or glassy rocks," and is divided by him into three features or factors,— (1) the degree of crystallization,—the crystallinity, (2) the magnitude or size of the crystal,—the granularity and (3) the shape and arrangement and mutual relations of the crystals and amorphous parts. This he calls "fabric." The discussion of the relative coarseness of grain or granularity has been of especial interest to me since the recent introduction of testing by diamond drill cores has given unusual opportunity to study the change in texture and granularity as one passes; from the margin to the center of the flow and this change in granularity is of very great help practically. It is not possible to separate, altogether, in discussion these three factors since we find that, generally speaking, near the margin the rock is likely to be more glassy and less crystalline, finer grained and with a different fabric. For instance, in many of the melaphyres the feldspars are distinctly thinner near the margin. There are, however, a few general remarks to be made concerning the texture or fabric before discussing the granularity in detail in Chapter IV.

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[6] In Mss. corrections Pumpelly changed "rubellan" to chlorophaeite."

[7] By a careless error this plate reads % of Ab instead of An, and the lines connecting ends of extinction curves with percentage scale are not accurately drawn. I think that these errors in the published plate do not affect my printed determinations (certainly not in most cases) as they are copyist's errors.

[8] p., 359, Fourth edition (1905).

[9] Neues Jahrburch (1904) Beilage Band XVIII, p. 155.

*Optical Mineralogy, p. 410.

[10] See Isle Royale Report. Figs. 23 and 29, and Fig. 16 of this report. Also A. N. Winchell, "Optical Mineralogy," pp. 359-360.

(1) *Crystallinity*. In rock so old as the Keweenawan rocks it would be hardly expected that very much glass would remain. It is, indeed, rare that one can, assume the presence of glass now, although there are many places in which it once existed and not infrequently small areas where it may perhaps still linger. It is not an easy question to say whether the change from glass to crystalline character is devitrification of a secondary nature which occurred ages after the formation of the rock or whether it may have taken place almost immediately, the glass having formed or having been kept at a temperature where devitrification could go on (that is, in the temperature of annealing as the glass manufacturers call it). Especially, where a glass forms close to the margin it may have been kept at a fairly high temperature for some time owing to the source of heat being in the center of the sheet. This is especially true when the outside or contact zone was allowed to heat up. Suppose, for example, an intrusion suddenly entering cold rock; it is quite easy to imagine in this case a rind of glass forming as the intrusion comes in and it is also quite easy to imagine a devitrification later, that is to say, as the contact zone heats up, the margin will be kept at a temperature where crystallization can go on. At the same time the material will be so viscous that the velocity of crystallization will be greatly checked and we shall have a peculiarly fine grained character. This is true, for instance, for a few inches of the Bad River gabbro sill exposed north of Bessemer. (See report for 1906, pp. 488 to 491.) Near the margin there are a few inches very fine grained and then it passes to a very coarse grain, perhaps extra coarse, very suddenly.

This is to me a reasonable explanation, not only of this fine grained marginal form of gabbro, but of some of the felsite ground masses, and it is a question whether a rock of this sort should be classed as originally crystalline or a devitrified rock. The irregular distribution of minerals or gases which tend to promote crystallization through the magma and their irregular escape also produce differences in crystalline texture, even after the rock for many purposes may be considered as solid,—for instance, capable of fracture. Whether indeed we may ever speak of a glass as absolutely free from viscosity is a question over which physicists would disagree although there is no doubt that in many cases the viscoscity is practically infinite.

(2) *The fabric*. In my Isle Royale report, I divided the textures into two groups according as they were characteristic of the central or marginal parts of the flows and we might also divide them according as they were characteristic of the salic or femic magmas and according as they were characteristic of the deeper seated or effusive forms. In this classification we may distinguish the following textures:

(a) *Central, femic, mainly effusive, ophitic*. This term I have used to denote a texture in which augite acts as cement or matrix and large patches often enclose idiomorphic feldspar in which the lateral pinacoid (brachy-pinacoid) is best developed and often the direction of the brachy-axis. An important feature of this texture is the fact that the feldspar has its form sharply developed against the augite. A. N. Winchell is inclined to lay the main stress upon this and thus broaden the use of the term ophite. His authority for so doing is derived from the first paper of Michel Lévy,[11] introducing the term, in which he uses the term ophitic. His arguments for his usage are given in the Bulletin of the Geological Society of America, Volume 20, pages 661 to 666. On the other hand I published quite a discussion in a foot-note on page 227 of the Isle Royale Report, of the two definitions, and in the Bulletin of the Geological Society of America, Volume 18, page 648, I gave a short note on the ophitic texture to accompany some illustrations from lantern slides of the ophitic texture as I understood it as a variety of the poikilitic, following the definition given by Michel Lévy in his "Structures et Classification des Roches Eruptives," page 28. The facts seem to be that Michel Lévy has used the term in a broader and in a somewhat narrower sense and that there has been fairly continuous use by two schools,—one using it in the narrower sense which will be found quoted on page 227 of the Isle Royale report. I translate it. "When the last element consolidated is a bisilicate (generally pyroxene) its areas without their own proper exterior form are larded with older crystals. Those of the feldspar notably are elongated in the direction of the edge between (001) and (010) and are flattened parallel to (010), and the ensemble takes a characteristic appearance which I have described and figured since 1877 under the name of ophitic texture." In the earlier paper upon which Winchell relies we find that more stress is laid upon the fact that the pyroxene "moule"[12]—acts as a mould or matrix for— the feldspar and the relative size of the two is not mentioned at just that point.

A few pages later, however, in the same article[13] he says "le minéral le plus charactéristique des ophites est le diallage en grands plages"—the most characteristic mineral of the ophite is the pyroxene in large areas.

Now before we settle upon the use of terms, the facts so far as they are known should be clearly in mind. In the first place, if we take a rock like the Greenstone, having the typical poikilitic ophitic texture in the middle of the flow where large areas of augite include perhaps hundreds of little feldspars, we shall find that in following the texture to the margin the augite decreases in grain much more and more regularly than the feldspar so that at a certain distance from the margin, while the feldspar still remains sharply defined in its own crystalline form and idiomorphic against the augite, it will no longer be true that several feldspars will lie in one grain of augite, but different grains of augite may be crowded in to fill in the spaces between the feldspars, so that in the same flow there will be transitions from a texture which is ophitic in the narrowest sense to one which is ophitic only in the broader sense.

Secondly, it will be also found upon comparing effusive and intrusive rocks that at least for the Keweenawan series there is a strong tendency for the feldspar to be relatively finer grained and the augite relatively coarser in the intrusive rocks. Thus while we occasionally find an ophitic texture in the narrower sense in intrusive dikes and sills, they have more predominantly the ophitic texture in its broader sense.

Moreover, in such intrusives it at times happens that while the plagioclase remains lath-shaped, the interstices are not filled wholly with a matrix of augite but with a eutectic inter-growth of quartz and feldspar.

The ophitic texture in the narrower sense is, then, more characteristic of the effusives. In both cases near the margin we find a gradual transition to a partly glassy or, as it has been called intersertal texture. But a matrix, glass or crystalline, of augitic composition seems to me important.

The probabilities are that it will be found a rather desirable thing to emphasize the relative size of the feldspars and the pyroxene and if ophitic in the broader sense is to be used to replace the term diabasic we mar have to introduce some new terms to replace ophitic in the narrower sense. In Idding's discussion of poikilitic texture[14] he recently proposes to subdivide the poikilitic texture, calling the matrix crystals, the oikocryst and the enclosed crystals chadacrysts, and giving a series of terms from per-oikic to per-chadic, according to the relative abundance and the relative size of the two. They may come in use. It is possible that some such term as poikilophitic may prove to be desirable and necessary, but it must be remembered that the rocks I call ophite and ophitic would also be called ophitic by A. N. Winchell, and in Rosenbusch's last edition (Vol. II, Pl. 4, Fig. 4) the illustration of ophitic structure is an admirable illustration of ophitic structure in the narrower sense in which I use it. It does not seem wise for me to make a change from my previous usage just now, especially as on the whole it seems to me that Michel Lévy, though he has used the term in both senses seems really to have the narrower sense mainly in mind and simply included rocks to which the broader term more directly applies: when they occurred in connection or as transition forms from the narrower sense. One must, then, remember that in this report the terms ophite and ophitic also imply luster mottling if the rock is fresh and the grain coarse enough. I would have kept the term luster mottled melaphyre, were it not very cumbersome when one wishes to add further descriptive adjectives and repeat the expression over and over again, as we must in the detailed sections.

A luster mottled texture is often visible in hornblendic rocks when it probably is a relic of the same texture in an originally augitic rock. For instance, just south of the road from Ishpeming to Negaunee about three-fourths of a mile east of Ishpeming is an amphibolite with 10 mm. poikilitic patches that I take to be an inheritance from an ophitic augite texture. In the contact zone of the Mount Bohemia gabbro and I think also in some coarse luster mottled rock south of the Porcupine Mountains the derivation in this way can be readily seen for we find the patches of augite changing to hornblende round their margin so that there is a rim of hornblende with an augitic less lustrous center.

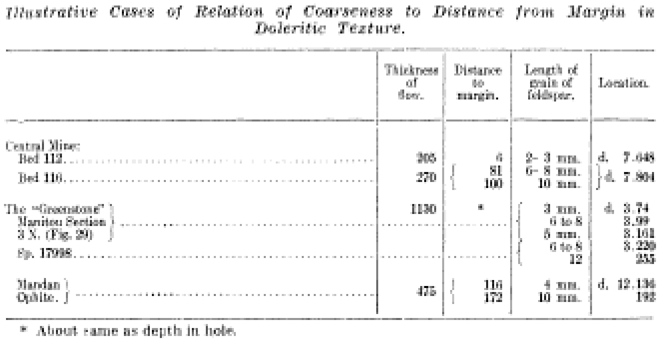
The augite seems to drive the corroded remnants of olivine before it in its growth. I suppose, too, that any interstices which were left would be between the different crystals of augite which seem to have been the last consolidation in a typical ophite. Thus when the rock is altered or exposed to weather the centers of the augite patches are the last to be affected and are left as knobs on the weathered surface as shown in Plates II and III of this report (see also Vol. VI) and as may be readily seen almost anywhere on Keweenaw Point but especially well on the Greenstone Range itself. This same knobby appearance is very characteristic at Mamainse in a heavy bed on the north side of Band Bay. On matte surfaces, such as pebbles or joint planes or diamond drill cores there is also a mottling,—the augite centers being often somewhat lighter-as seen against a darker green chloritic or reddened ground (Pls. IV and VI) but the exact color pattern may vary. The weathered portions may sometimes be browner. One can thus with a little training recognize without any thin section the gradual increase in grain of the augite, and the rocks which show this mottling are very monotonously the same, even under the microscope differing, so far as I can see, but slightly. Some have a little more or little coarser olivine remnants. Occasionally this ophitic texture may be combined with large feldspar phenocrysts (eocrysts). This is true sometimes in the foot of the Kearsarge lode and occasionally in the Greenstone itself.

Figure 17. Illustrating original cavities in rock of the copper bearing series such as may have been originally filled with gases. In the figure they are wedged in between feldspar laths and octagonal augite,—characteristic of the doleritic texture panidiomorplin. Reproduced from Figure 7, Annual report for 1903, p. 245.

A very good large colored diagram of the ophitic texture is given in Irving's Monograph,[15] Plate IX, which shows pretty well in black and white reproduction (Pl. IV. c). Before leaving the subject of the ophitic texture it may not be inappropriate to mention its derivation from the Greek word for reptiles—ophidians—and in Plate IV a I reproduce for comparison a photograph of a Gila monster which Mr. Jesse Myers kindly took for me.

(b) *Doleritic* (Pl. VII, Sp. 17998). This term I used in the Isle Royale report for a texture in which the feldspar was much coarser relative to the augite than is generally true in the ophite. The term *doleritic* has always been applied to rather coarse grained rocks of the basaltic and diabase families. A recent suggestion has been to apply it to rocks of these families in which the feldspar can be easily recognized with the eye or the lens, while hornblende or pyroxene cannot. This is the definition suggested by Iddings, Chamberlin and Salisbury in their Geology, Volume I, p. 417, and adopted by Pirsson ("Rocks and Rock Minerals," p. 198). It is obvious that nay definition of the texture is not out of harmony with this macroscopic definition since if the feldspar could be recognized and the pyroxene not, it would be likely that the feldspar would be relatively coarse, though perhaps not really in larger grains than the augite, since it is easier to recognize feldspar with characteristic twin striations than to separate augite from hornblende. It is, however, true that I have applied the term "doleritic texture" and "doleritic streaks" in my descriptions of the cross-sections (cf. Isle Royale, drill hole III, Sp. 15126) to specimens which Pirsson might call "gabbro," e. g., that figured in Plate VII, that are so coarse that both the feldspar and the augite can be distinctly recognized by one who is practiced. The fact is that one will find in the heavier beds (more frequently in some than in others) streaks which appear to be almost sharply separated from the rest of the rock. In many cases they might readily be taken for intrusions and yet if one will study one will find that there is a definite connection between their coarseness and the coarseness of the surrounding rock, and that they never occur very close to the margin,[16] and will, I think, finally conclude that they are due to some sort of differentiation by which some of the ingredients have gathered together in the process, of cooling and produced a magma more favorable to the coarse crystallization of the feldspar. This may be due to some such action as that which produces a stratification banding in water with very finely divided clay slowly settling in it, but I am more inclined to think that it is due to the accumulation of some sort of mineralizer, say water vapor, or the like, in certain layers. There may be a distinct tendency toward separation of the water bearing and non-water bearing magma. In some of the large exposures of the Greenstone, say back of the Central mine, one will find broadly curved bands of lighter and darker color, which appear like the stratification of some gneisses, but these are evidently nothing more than eutaxitic flow lines, possibly marking some initial slight difference in temperature which has been rendered permanently visible by slight differences in the abundance of certain crystals. The phenomena are very well described (and without any such theoretical preconception as might tempt me to warp my account), by Marvin in his description of the light and dark kinds of diorite by which he cuts the "Greenstone" up into the different beds of his Eagle River section 91 to 108.[17] All of these belong to one immense flow. That feature Marvin does not seem to have grasped. He describes two types,—the light type and the dark type, and these alternate over and over again. Beds 90 to 91 represent the finer grained ophite near the margin and Beds 92 and 93 a coarsely mottled rock of the ophite type; from Beds 94 to 106 there is a pretty regular alteration of what he calls the "light type" and the "dark resinous type,"—the light being what I should call "doleritic," the dark resinous type being the "ophitic" or "luster mottled." This is, however, the coarsest possible illustration of the texture in a rock which might be by many considered as a gabbro, *but if so it is an effusive gabbro*. The feldspar here in the light type is long and, as he says, at times over an inch in length. The plagioclase twinning lines are so coarse that he noticed them. He suggests that the relative proportions are 40 to 54% feldspar, about 40 to 46% (he calls it hornblende) augite, and considerable delessite (including the altered olivine?) It has a coarse crystalline, irregular texture with numerous segregations of coarser material composed of prehnite and feldspar and quartz and epidote, all sugggesting a rock originally rather porous, and my explanation is that in the process of the crystallization the gaseous mineralizers, being collected in certain streaks, produced a coarser crystallization of the feldspar and a more open miarolitic or interstitial character. These interstices may be lined with borders of fibrous chlorite or chalcedony. The main filling may be as described by Marvin or the interstices may be filled with chlorite and quartz, apatite needles, and various specks of iron oxide. Against them not only is the feldspar sharply bounded by the augite but may often be seen to have its crystalline form. Figure 7 of Report for 1903, herewith reproduced as Figure 17, illustrates this, and Figure 3, Plate VI of Volume VI which is a photograph, not a drawing, shows the same thing, not so sharply and more or less disguised, with a tendency toward an agglomeration of the feldspar. Close to the center of the field and a little down to the left is a cavity between three fairly large feldspar crystals which is lined with the fibrous chlorite rind. The filling of these interstices might properly be called secondary but in some cases, no doubt, the filling began long before the rock had lost its original heat. Indeed, it may have been pretty closely associated with the original cooling. If I am right in thus regarding these streaks and this texture it is a superficial equivalent to deep-seated pegmatites and similar rocks. The tendency to this doleritic texture seems to be characteristic of some beds more than of others and these doleritic streaks appear at times to be fairly persistent. Borne engineers have correlated from drill hole to drill hole by them, but if I am right as to their origin such a correlation is unsafe. Yet their presence is a pretty sure sign of a rather heavy flow and correlation can often be made by this fact.

One thing I would emphasize before leaving this subject and that is that while the grain varies in these doleritic streaks and is not always uniform as compared with the more luster mottled rock in which they may often occur, yet after all, in a broad way they too, are coarser the farther they are from the margin of the flow, and whereas near the margin we may find little doleritic streaks in which the feldspar is two or three millimetres long, in the larger flows it may be several millimetres or as Marvin says an inch. The characteristic feature is not the absolute size of the feldspar but its size relative to the augite and to the feldspar of the surrounding, not doleritic, rock. To this we may add the tendency toward idiomorphic character in the augite and open interstices. For illustrations of this tendency of the doleritic streaks to be coarser in the coarser flows, and coarser near the center of those, see Beds 112 and 116 of the Central mine section, Belt 42 of the dark-Montreal, as well as the "Greenstone" especially in its upper part.



Illustrative Cases of Relation of Coarseness to Distance from Margin in Doleritic Texture.

	Thickness of flow.	Distance to margin.	Length of grain of feldspar.	Location.
Central Mine:				
Bed 112	205	6	2- 3 mm.	d. 7.048
Bed 116	270	81 100	6- 8 mm. 10 mm.	d. 7.804
The "Greenstone" Manitou Section 3 N. (Fig. 29)	1130	*	3 mm. 6 to 8 5 mm. 6 to 8	d. 3.74 3.99 3.161 3.220
Sp. 17998			12	255
Mandan Ophite.	475	116 172	4 mm. 10 mm.	d. 12.136 192

* About same as depth in hole.

(c) *Glomeroporphyritic or navitic*. (Pl. VII, Ss. 15384, 15295). The appearance under the microscope of this texture is illustrated in Figure 4 of Plate VI of Volume VI and also in Rosenbusch's Figure 1 of Plate IV of Volume II, though that is not really highly characteristic. In Irving's Monograph, Plate IX, Figures 2 and (especially) 3 this texture may be represented. It is characterized by the fact that the feldspar occurs with very considerable range of size and the larger feldspars tend very strongly to gather together into bunches or clots. To this the word *glameroporphyritic* applies, which we may paraphrase as agglomerated porphyritic or clotted. Iddings well calls it seriate porphyritic. The origin of the texture seems to be in the fact that there was a considerable excess of feldspar molecules in the cooling magma so that the feldspar crystallized before the magma came to rest, and grains stuck together more or less. The feldspar growth seems to have been continuous and these larger feldspars which rolled in from perhaps a cooler point in the course of the flow may be toward the margin considerably larger than in the grain which would result from the very last consolidation. (Cf. Pl. VII.) In a glomeroporphyritic flow there may thus be a very considerable hiatus between the two kinds of feldspar near the margin and an almost continual series toward the center with every gradation between what Iddings calls the seriate and hiatal fabric. These feldspars do not seem to be radically different in chemical composition or widely separated in time of origin from the latter feldspars. Nor are they generally speaking corroded. They are what I have called rhyocrystals and not brotocrystals. Larger and distinctly hiatal crystals with no transition to the crystals of the ground mass do, however, occur and are characteristic of certain beds. One of the most important of these is the foot wall of the Kearsarge lode. (Pl. VII, Sp. 17956, and Mandan d. 18 at 90 ft.) The glomeroporphyritic is a type of texture which occurs especially in the Ashbed series; for instance, in the beds near the Pewabic worked by the Quincy mine, but some signs of this texture occur all through the series in many of the more feldspathic melaphyres, especially in a group below the Wolverine sandstone in the Central mine section, Beds 97-115, in the Torch Lake Mining Company section, Beds 30-59, Holes 4-7.

(d) *Porphyritic hiatal*. (Pl. VII, Sp. 17956 and Mandan d. 18 at 90 ft.) We have just spoken of this texture in contrasting it with the glomeroporphyritic. It must not be imagined that in this texture feldspar individuals do not occasionally group themselves together. Almost all plagioclase is a group of twins, but in this texture the difference in size and shape and sometimes chemical character between the crystals of the older generation and the crystals of the younger is much more marked than in the glomeroporphyritic or seriate porphyritic texture except possibly near the margin of a flow, for in the latter, where fine grained, very close imitation of the hiatal porphyritic fabric may be found. The fabric I have now in mind is one in which the porphyritic feldspars are found several millimetres, in fact at times centimetres long, while the feldspars of the ground mass may not be recognized with the naked eye. In fact, such rocks are very likely to have a peculiarly fine grained blue-black, dense, aphanitic ground mass and such blue-black traps can often be recognized even when phenocrysts are not present. In other words, these rocks are distinctly magnophyric in Iddings' use of the term, while the glomeroporphyritic rocks are normally, but not always, mediophyric.

All the above textures apply primarily to the basic or femic rocks. The salic rocks have their own textures but so far as the phenocrysts are concerned all are much more porphyritic hiatal. Though the phenocrysts may be of any size they are usually sharply distinguished from the ground mass. The ground mass of the felsites is usually a fine grained mosiac of quartz and feldspar but sometimes the quartz becomes poikilitic by simultaneous extinction showing an orientation over areas which include a lot of other things enclosed, such as feldspar and iron oxide. Not infrequently these poikilitic quartz areas surround phenocrysts of quartz, as with an aureole or halo. I am inclined to believe that these textures of poikilitic quartz are due to secondary alteration of an originally glassy ground mass. Coming now to textures involving more especially ground mass:—

(e) *Amygdaloidal* texture (Pl. VII, Sp. 17956) is due to gas bubbles more or less filled. These bubbles are abundant at the margins and tops of flows. Occasionally large ones seem to occur also well in toward the center. It is not infrequent to find beds of fine grained red mud or ash filled with what seem also to be practically amygdules produced by the turning of the water in the mud to steam through the heat of some overlying bed. The bubbles are larger and rounder in the ophites, smaller and finer and often more drawn out in the more feldspathic rocks. Around the amygdules, as near the margin of the flow, the grain becomes finer; the feldspar assumes forked and skeletal formes such as are according to Tammann[18] characteristic of crystallization which takes place quite a little below the fusion point. From the bottom of a flow these bubbles may rise up in long tubes, the so-called pipe amygdules. Such pipe amygdules are well exposed, for instance, in the bluffs just north of Bessemer. Thus there may be a little of the lower part of a bed which would be classed strictly as amygdaloid,—generally, however, not over a foot or two. In the various sections it has been found convenient and necessary to assume that the 4 top of the amygdaloid was exactly the top of the flow.

(f) *The microlitic* texture which occurs around amygdules and elsewhere is shown in Figure 5 of Plate VI, Volume VI, and in the plate already referred to in Irving, and in Figure 5 of Plate III in Rosenbusch's Physiography. It is characterized by the fact that the last generation of ground mass is composed of feldspar in minute needles perhaps something like 0.1 millimetre long and very much more slender. Instead of being tabular they are more likely to be prismoidal.

There are a number of textures here which may perhaps be distinguished but which are so closely alike that it is hard to describe the difference. Many of the melaphyres have close to the margin a microlitic texture when the augite remains still in the glassy form. This also, occurs around amygdules. In either case there is really more feldspar in the rock and so we get feldspar porphyries with a very similar texture. In the extreme marginal forms, however, the feldspar microlites are almost invariably forked and are inclined to enclose glass and assume skeletal shapes, and are perhaps on the whole a little less likely to be regularly arranged. This is perhaps the hyalopilitic texture proper and may be found in most of the sections which are cut within a few inches of the margin. I have never seen it when the record implies that it was more than a foot away from the actual exterior of the flow.

On the other hand, a texture which is rather characteristic of the feldspar porphyries is liable to have the feldspar somewhat coarser and especially to have the feldspar crystals arranged in somewhat parallel flow lines. A particularly good illustration of this is found in a feldspar porphyry which seems to cut an ophite in the Mendota cross-section.

(g) *The vitrophyric texture* (generally glassy ground mass) seems usually to be confined to a few millimetres from the contact. In the femic rocks, the melaphyres and porphyrites, this is probably as far as it went. In the felsites and salic rocks it extended much farther. In the basic rocks it is brown and yellow and seems to be largely decomposed.

(h) *The normal crystallization* of the quartz feldspar eutectic, if it crystallizes directly from aqueous solution in the first place, seems to be in the rock intergrowth which I have called micropegmatite. A good adjective perhaps is *graphic*. The texture is beautifully illustrated in Iddings' chapter on the "Crystallization and Texture of Igneous Rocks." When microscopic, Iddings calls it micrographic. This micrographic texture occurs in the interstices of the Bessemer gabbro and the center of most, if not all, of the large diabase dikes.[19] It also-occurs in some of the porphyries. It is also very common in the pebbles found in the conglomerates. It is so much more common there than in the igneous rocks that it is a strong argument in favor of Wadsworth's view that it may be a secondary texture of the same nature as the poikilitic aureoles of quartz and the quartz feldspar mosaic of the felsite. Irving agreed with Wadsworth in his interpretation. I can not personally agree with that interpretation, for reasons explained quite fully in my discussion of the quartz diabases and the granophyric diabases (which Iddings would call the graphophyric diabase), in my Isle Royale report, but the relative abundance of this texture in the pebbles is certainly puzzling. Can we assume that it is primary and also secondary in the presence of hot water?

(i) Another texture of the salic rocks is the *spherulitic or micro-felsitic*. In some of the porphyries near the Bare Hills described by Hubbard, the rounded balls, known as spherulites, occurring in the felsites are very well shown. These also occur in the Porcupine Mountain porphyries. It is due to the rapid growth of quartz feldspar eutectic from centers of crystallization in a salic magma and is sometimes, perhaps always, a microscopic or submicroscopic radial intergrowth of quartz and feldspar aggregate in the micrographic texture. This is very fully and beautifully described by Iddings.

(j) Another texture characteristic of the salic rocks is a granular aggregate of quartz and feldspar, none of the grains being peculiarly elongate and the general effect being that of a *mosaic*. This occurs in the gabbro aplites and is pretty surely primary. I am inclined to think that a very similar texture but without quite so much sign of crystalline form in the grains also occurs as a product of secondary alteration. This mosaic texture is then sometimes pan-idiomorphic and sometimes hyp-idiomorphic. The general appearance is equi-granular. (Report for 1908, Pl. VII, Fig. 5.)

(k) Before leaving the subject of textures one texture which is characteristic of the sediment should be mentioned, that is the *tufaceous* in which the peculiarly concave forms of ash is well illustrated as shown in Figures 1 and 2, Plate VI of Volume VI. The original fragments are found entirely replaced and may be charged with epidote, but before this change they may have been coated with chalcedony from the large amount of soluble silica which necessarily occurs in a glass deposit which then persists so that after their original substance is all gone their form may yet remain. This leads to one further texture.

(l) It will often be found that between crossed nicols there are large patches which extinguish together, are generally quartz full of enclosures, and have no relation to the texture as seen in ordinary light, in which latter case one may perhaps plainly see the outlines of feldspars arranged in some microlitic or trichitic texture. Upon changing to polarized light there will be no sign of this texture remaining. This is a *secondary poikilitic*,—metapoikilitic texture.

In the Isle Royale report I separated the petrographic notes from the general cross-sections. It has on the whole not proved a satisfactory method and in this report I have placed petrographic notes with the general notes where they naturally come in describing the cross-sections. The most complete and systematic set of thin sections are from Isle Royale drill cores. Since then sections have been made only as some special point of interest came up. The following list of specimens may with the index help one in knowing what specimens have been collected or sections studied from various horizons.

§ 4. LIST OF SPECIMENS OF KEWEENAWAN FROM SP. 15000 ON.

Ss. 15000-16000	*are from Isle Royale and mainly sectioned. The sections are in the Ashbed and Central Mine group of flows. Up to 16400 they were also from Isle Royale, mainly not sectioned.*
Ss. 16401-16473	*are from Tamarack No. 4 shaft Down to 16445 mainly Ashbed group, down to 16457 above Conglomerate 14. (See Annual Report for 1903.)*
Ss. 16474-16482	*and 16490-16500 and Ss. 16515-16534 are Tamarack No. 3 shaft down to the Allouez Conglomerate No. 15 at 16500.*
Sp. 16483	*is from Tamarack No. 5 shaft, continued by 17654-17686.*
Ss. 16541-16564	*are from Centennial cross-cut, Calumet to Osceola.*
Ss. 16650-16676	*are from the Central Mine. (Fig. 31).*
Ss. 16677-16679	*are from Eagle Harbor, section 23, T. 58, R. 31.*
Ss. 16780-16782	*are from the Copper Falls Mine.*
Ss. 16873-16880	*are from T. 58, R. 32, Ashbed group.*
Ss. 16906-16907	*are from Copper Falls, Central section.*
Ss. 16908-17057	*are from the Lac la Belle and Mendota section (See Vol. VI, Pt. 2,—a number of thin sections).*
Ss. 17058-17132	*are from a long cross-cut from the Quincy Mine running below it in the lower Ashbed and Central Mine groups. Only one section 17066,—an ash.*
Sp. 17133	*is from Keystone Location. (Sec. 30, T. 58, N.37 W.) sectioned; also 17213-4; otherwise—*
Ss. 17134-17236	*were further specimens in T. 58, R. 28, for Hub-bard's work on Bare Hill, etc. (Vol. VI, Pt II.)*
Ss. 17275-17342	*are from the Franklin Junior section (See Vol. VI, Pt. II) continued by*
Ss. 17343-17448	*Mt. Bohemia rocks for L. L. Hubbard (see Vol. VI, Pt. II).*
Ss. 17449-17551	*are along lines of contact with occasional sections. Porphyry, melaphyre, dolerite, ophite, amygdaloid, felsite, tufa.*
Ss. 17552-17553	*are from Section 33, T. 58 N., R. 31 W.*
Ss. 17554-17635	*are miscellaneous specimens.*
Ss. 17636-17653	*are from Franklin Jr. cross-cut (See 20429). Figure 40.*
Ss. 17654-17686	*are from Tamarack 5 shaft.*
Ss. 17686-17689	*are Gratiot Bluff felsite.*

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[11] Bull. Soc. Min. Francaise, Vol. VI, 1878, p. 157.

[12] Pits the feldspar as dress of the present fashions fit the female form. I notice the word used in that connection in French. A. C. L. 1909.

[13] Loc. cit. p. 169.

[14] "Igneous Rocks," p. 202.

[15] U. S. Geol. Survey, No. 5.

[16] Though occasionally, e. g, in Bed 35 of the dark-Montreal section (Chap. V. §2) it seems as through the hot welding of two flows had given a doleritic texture. The original contact representing a cooler streak in the joint bed should be extra coarse in grain.

[17] Vol. I; pt. II, pp. 133-137. Van Hise and Leith doubt that they are "one flow."

[18] Kristallisieren und Schmelzen, Leipzig, 1903, pp. 134-135.

[19] See Vol. VI., Pt. I., Pl. XVI and report for 1908, Pl. VII.

Ss. 17690-17695	are near South Range near hill north of belt.
Ss. 17695-17715	are various specimens in Ontonagon district, a few of them sectioned. 17705 is a glomeroporphyrite.
Ss. 17715-17865	
Ss. 17866-17871	Copper vein, prehnite, melaphyre boulder.
Ss. 17878-17899	Atlantic Mine cross-cut. Chapter V, § 16
Ss. 17899-17991	Franklin Jr. (See 17342) section and drill holes sections Nos. 17982, 17991. Figure 40.
Ss. 17992-17999	Drill cores, Manitou holes.
Ss. 19401-19703	are between Winona and Rockland, described by P. S. Smith, typewritten. A few thin sections have been made with notes by Lane.
Ss. 19704-19775	West of Ontonagon.
Ss. 19735-19740	Old Colony cross-cut. Chapter V, § 10.
Ss. 20039-20340	Black River section with Gordon's notes. (Report for 1906.)
Ss. 20351-20354	Ashbed group on south side of Portage Lake, Section 35, T. 55 N., R. 34 W.
Sp. 20356	Sectioned eastern sandstone, Wyandotte drill hole 13. Chapter V, § 21.
Sp. 20357	Amygdaloid conglomerate, Wyandotte drill 9.
Sp. 20358	Sectioned, epidotic sediment, Wyandotte drill 5.
Sp. 20359	Section of datolite, Winona Mine.
Ss. 20380-20427	Superior trench and shaft. Chapter V, § 14.
Ss. 20429-20442	Franklin Junior, 4th level cross-cut, of Section 17653. Ch. V, § 11.
Ss. 20443-20446	Franklin Junior, 21st level cross-cut. Ch. V, § 11.
Ss. 20447-20458	Miscellaneous illustrative specimens from various locations.
Ss. 20461-20485	Manitou section.
Sp. 20485	M. 3. 122.
Ss. 20486-20500	Mendota ophite and intrusive felsite porphyrite.
Ss. 20501-20559	Mount Bohemia.
Ss. 20560-20562	
Ss. 20563-20598	Torch Lake sections, 20575 Minong type. Ch. V, § 10.
Sp. 20600	Altered boulder of Calumet and Hecla.
Sp. 20601	Copper and silver from Old Colony lode.
Sp. 20602	Calcite and copper in two generations.
Ss. 20617-20620	Diamond drill core set, used in Plate VI, from St. Mary's Challenge exploration.
Ss. 20623-20638	Calumet and Hecla White Pine explorations.

Descriptions of the following thin sections will be found scattered through the text.

Sp. 19086	
Sp. 17982	Steamed sediment.
Sp. 17998	(Oligoclase Ab An.). Into the hanging of the Pewabic Lode.
Sp. 20356	The earlier sandstone. Marvine's Conglomerate 6-8, or sediment.
Sp. 20358	Wyandotte Hole 5 at 307.
Sp. 20359	

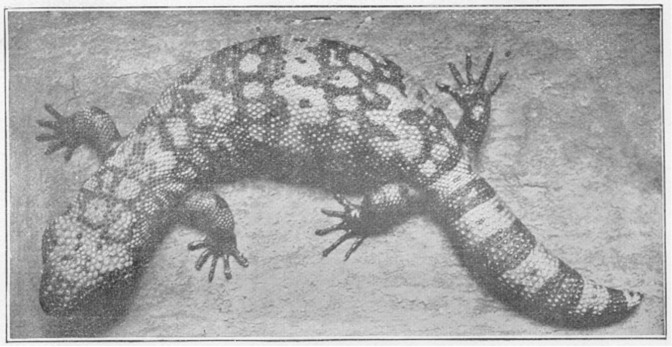

Plate IV. (A.) Photograph of an ophidian, the Gila monster, taken by Jesse Myers of the Zoological Department of the Michigan Agricultural College.

Plate IV. (B.) Ophitic mottling brought out near a seam of chlorite from the Manitou section 3 D, 3 N., at 543 feet depth; in the greenstone, the base of which is about 72 feet away. The diameter of the core is 7-8 of an inch.

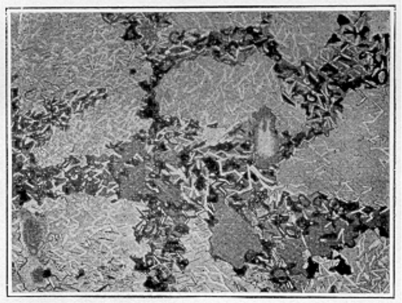

Plate IV. (C.) The effect of ophitic texture in thin section, half-tone reduction of Plate IX, Monograph V, U. S. G. S., by R. D. Irving. From a melaphyre in the southeast quarter of Section 9, T 51, R 12, Minnesota, enlarged about 4.7 in diameter.

CHAPTER IV. THE GRAIN OF THE IGNEOUS ROCKS.

§ 1. INTRODUCTION.

This chapter logically belongs with the chapter on microscopic petrography but the grain or coarseness of many of these rocks can be made out without the use of the microscope. Since its variation has practical importance and as I have made some especial study on the same, it has seemed to me best to make a separate chapter of my studies.

Igneous rocks, as their name implies, have been formed through the loss of heat, aided or retarded by changes in pressure and included gases (mineralizers). Treat heat or caloric (the ancient phlogiston) as an imponderable substance, and we may group it with the gases as a solvent, and say that consolidation is largely or wholly due to diffusion of solvents through the margin. In other papers[1] I have discussed the general theory of the matter, but as some of them are out of print and the report for 1903 is; defaced by a number of errors in printing, I will give an abstract here correcting some errors but omitting details.

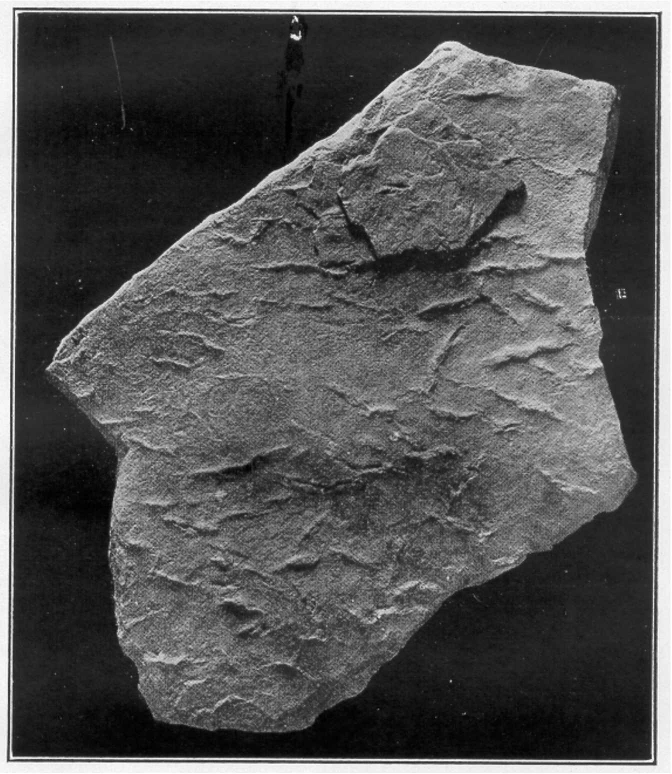

Plate V. Tracks (?) on a slab of Nonesuch shale, photographed by J. T. Reeder. Dimensions of slab about 10 x 14 inches.

The Keweenawan rocks most often occur in dikes, sills, sheets and lava floods,—forms, one of whose dimensions is so much less than the others that the position and distance from the margin in this direction is the important factor. It is not the only important factor, for the chemical character is, of course, of fundamental importance. The more viscous (practically the more feldspathic) the magma, the finer grained. The process of growth may be stopped in one of two ways, either the available molecules are exhausted or the magma becomes so viscous that they can no longer be pulled out. In the former case it may be simply that the rock is all consolidated and wholly crystalline, the mineral in question being the last one formed. It may also be that the remaining molecules are soluble at a given temperature and pressure and may go into entirely different crystal molecules, and indeed the crystals formed may be redissolved. For instance, we find plain indications in the Keweenawan rocks that a magnesium silicate forms as olivine at high temperatures, but that if the part molten rock remains near certain lower temperatures long enough the olivine already formed may be corroded and augite molecules formed instead. Thus for a certain distance in from the margin the olivine may be sharp and conspicuous, and farther in may be only in corroded grains.

One important factor, however, will be the rate of cooling. For as the rock fluid or magma cools it tends to become more viscous and that retards both the formation of centers of crystallization and the flow of molecules to them and in general for a given composition of rocks the slower the cooling the coarser will be the grain. In the viscous feldspathic rocks the power of crystallization is low. Hence feldspathic rocks are extra fine grained. On the other hand augitic rocks of a composition something like Bunsen's normal basalt are always visibly granular within thirty feet of the margin. Felsites in similar masses will be recognizable by their porcelain-like fineness.

The retention of solvent gases seems, as we have mentioned in discussing the doleritic and ophitic or poikilitic texture, also to aid the power of feldspar crystallization, so that the last formed feldspar is likely to be coarse relative to the augite in intrusive, pegmatites and doleritic streaks. On the other hand, it appears that the surface melaphyres flowed and kept pretty well stirred up in temperature until they were cooled to within 10 per cent of the crystallizing point of augite, and that consolidation took place from the margin to the center before the center had cooled much,—for the grain of the augite (as theory would lead us to expect in such a case) increases from the margin to the center. Theoretically, we should find that there could be a rapid rate of increase proportional to the distance from the margin for a short side zone which was crystallized before the adjacent rock had heated up appreciably and there would then be a transition (fairly sharp) to a slower rate of increase. This, if the degree of supervision is small, and the initial temperature not over 5 per cent more than the crystallization temperature, will continue from the margin to the center and be proportional to the distance from the outer margin of the contact zone. The augite of the Keweenawan melaphyres which crystallized really followed these laws to a rough degree of numerical accuracy. The contact zone and rapid rate of increase is confined to a belt usually less than ten feet. The inner rate of increase (which I have called A, the outer C') is fairly uniform for any one flow[2] and in the lustre mottled melaphyres or ophites is usually between 1 mm. in 10 and 1 in 20 feet, or say 1 mm. in 3 to 5 meters. In the more feldspathic flows, like the Kearsarge foot, it is less. The maximum rate of increase must depend on the ratio of viscosity and consolidation. The very highest inner rate of increase is a rate of 1 mm. for each 8.5 feet, but in the large majority of cases the rate comes out 1 mm. in somewhere between 11 and 16 feet. This refers to the linear diameters of the augite grains as indicated by the mottlings on the drill cores. (Pls. IV and VI.)

§ 2. GRAIN NUMERICALLY DEFINED AND RECOGNIZED.

To take up this matter more precisely, while we know that some rocks are coarse grained and some fine grained, just as grocers sell coarse and fine granulated sugar, it is not at all necessary that all the different minerals that make up a rock should be of the same grain. This is not generally true. It is also quite possible that in comparing different parts of one rock mass, one mineral may be coarser, another finer. Whether this is so is a matter of observation. In any precise work the grain of one mineral must be considered at a time. Still it is. a matter of common observation that some rocks like pegmatites have a generally coarse effect, others mineralogically alike, aplites say, are generally much finer grained.

The coarseness of grain of a given mineral may be determined by the linear dimensions of its crystals or by the areas covered by them in cross-section.

Practically, it is generally more rapid and convenient to compare linear size,[3] though the areas appear to vary more directly with the slowness of cooling.

The grain of a mineral may then be determined by taking the average of breadths of the grains. I have sometimes used the average of five of the grains (making sure of full-sized ones and not working on clipped corners, by taking the largest within a given area large enough to include numerous grains, like the field of view of the microscope, or a square centimetre, etc.). Another way of measuring the grain is by varying magnification. If one section, magnified five diameters, appears as coarse as another, we may say its grain is one-fifth as coarse. In the Isle Royale section most of the work was done with a micrometer eye-piece, one of whose divisions was about equal to 1/30 mm. So I took three observations, for by adding them and pointing off two places one can get the average dimensions in mm. at once.

The grain of a rock we may regard as the grain of characteristic and dominant constituent minerals. If it is to be studied with relation to the margin of an igneous rock it is important that the mineral should be one which formed after the fluid rock magma came to rest. The last formed constituent is generally that which conforms more closely to the laws of cooling, for (1) heat given out by chemical rearrangement is less and (2) even its own latent heat of crystallization is taken up largely by pre-existing minerals and thus disturbs the simple cooling effect less; (3) the abundance of granules already present tends to prevent undercooling and bring on crystallization promptly, as fast as the temperature drops so that it is possible; (4) initial irregularities in temperature are more likely to have been smoothed out.

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[1] Bull. Geol. Soc. Am., Vol. VIII. (1896), pp. 403-407; Geol. Rep. on Isle Royale (Geol. Sur. Mich., Vol. VI., 1898), pp. 106-151; Am. Jour. Sci. (4), Vol. XIV. (1902), pp. 393-395; Bull. Geol. Soc. Am., Vol. XIV (1903), pp. 369-406; Ann. Rep. Geol. Sur. Mich, for 1903 (1904), pp. 205-237; Do. for 1904 (1905), pp. 147-153, 163; Am. Geol. Vol. XXXV. (1905), pp. 65-72; Jour. Canad. Mining Inst., Vol. IX; "Die Korngrösse der Auvergnosen," Suppl. to Rosenbusch Festschrift (1906); Report Geol, Sur. Mich. (1908); U. S. G. S. Monog. LII, p. 407.

[2] Cf. the data found for the Greenstone, especially at the Mandan and Manitou locations.

My most important and interesting results have been obtained on the augite which is the last formed essential ingredient of many of the traps,—those that run about 48 per cent silica and 10 per cent lime, such as are very common in the Keweenaw series. It is the cement or mesostasis.

The size of grains of this augite is often quite readily recognized with the naked eye. Of course it can always be told in fresh rock by examining thin sections under a microscope. It may also be recognized without the microscope:—(1) by the flashes of light reflected from the large faces which extend all over one individual. Rocks so reflecting have been called luster mottled melaphyres and ophites. They are poikilitic. (2) Again the iron oxide and olivine seem to have been crowded away from before the augite as it formed, though the feldspar is enclosed. Possibly there is some porosity between the grains. There should be. Thus the alteration to chlorite and serpentine always begins at the outside of the augite and works in, and as we have mentioned there are color patterns formed which are recognizable to the practiced eye,—sometimes on joint planes, sometimes; on smoothed surfaces, whether polished or unpolished, rounded pebbles or as illustrated in drill cores. They are more faint on fresh fractures, but even here there is a faint purple and green mottling often mentioned by Marvine. In general the augite centers are less greenish.

(3) If the rock is exposed to the mechanical erosion of the rain, the interstices weather back and leave a warty, pock-marked appearance so that the rock fifty years ago was called varioloid greenstone. Illustrations of the appearance of the drill cores and of the weathered surface are found in Plates II to VII.

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[3] Rosival (Verb. Wien Geol. Reichs-Anst, XXXII, 1898, p. 143) has demonstrated that volumes are proportional to linear measurements of mineral grains in section, as A. N. Winchell has called to my attention.

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§ 3. GRAIN DEPENDENT ON RELATION TO THE MARGIN.

When igneous rocks occur in elongate forms, over five times as long as thick, the distance from one margin alone need generally be considered. There are exceptions, however, to this, as when gas escapes into a cavity (a bubble which when filled is an amygdule) around which we find in consequence a finer grain. The doleritic streaks due perhaps to segregated mineralizers are other exceptions. Occasionally (Sp. 15743) we find a finer grain near a crack which might be explained by supposing that the rock was a stiff viscous glass and cracked in cooling like the basaltic columns before crystallizing.

When a rock crystallizes there are two factors concerned. The one is the power of crystallization, to wit, the number of crystal granules forming in a unit volume in a unit of time.[4] If, for instance, we heat up a glass above a certain point it will commence to devitrify and the higher we raise the temperature the more rapidly will it devitrify and the more numerous will the specks of crystalline devitrification become. Obviously the number of these will put a distinct limit on the size of the crystal into which any one center may grow. This is known as the power of crystallization.

If the substance has not high power of crystallization it may be cooled so rapidly that it becomes a stiff solid glass and the crystals will not appear at all. Then upon raising the temperature we shall find that at some temperature, often about that at which the glass begins to soften, the crystalline centers appear. The temperature where there is greatest power of crystallization is sometimes considerably below that of perceptible viscosity, sometimes much higher and nearer that of the fusion point. The power of crystallization always seems to decrease near the fusion point, but this must be partly, at least, because the latent heat of crystallization is given out and raises the surrounding fluid to the fusion point and so checks the action. The power of crystallization is not so inversely proportional to the viscosity as the velocity of crystallization.

This second factor is the rapidity of crystallization or linear velocity of growth of crystals in millimetres per minute. This differs in different directions. We ordinarily assume that the planes of cleavage are planes of greatest molecular density. It is natural to infer that in attractions lying in these planes the molecular attractions will be strongest and there will be a tendency to greater growth. This is, indeed, true in a general way. Minerals which have an ample supply of material generally are elongated and grow out fastest in the direction of cleavage. If there are two cleavages concerned, the direction of elongation is most likely parallel to their intersection. That this is not the only factor concerned, however, and that the mutual attractions of various crystal atoms and molecules play a part is shown by the fact that crystals have different forms when crystallizing from different solutions and that minerals which have very poor cleavage,—for instance, quartz—very often have a marked tendency to elongation. However, it is so generally true that we may rely on it with some confidence that crystals which form rapidly with an ample supply of nourishment are elongate. This is particularly characteristic of the feldspars. Near the margin of a flow the very small and minute feldspars of the so-called microlitic and trichitic texture are, as will be seen from the measurements given in the Isle Royale section, perhaps five to ten times as long as they are broad, and in such feldspars the elongation is often parallel to both of the cleavages. In the coarser feldspars, elongation is likely to be more than three times that of the breadth and the form is more that of a tablet. It is true also of the augite that even in the grains which form the last interstitial patches there may be often discerned a distinct tendency of elongation parallel to the vertical axis and to the cleavages. Now, obviously, if the different individual grains of a mineral are idiomorphic and not interfered with by others their size in different directions must depend very largely upon this velocity of crystallization. This velocity of crystallization is, however, in some cases at least, not independent of the temperature itself. Apparently it increases as the temperature falls below the temperature of saturation or fusion and attains a constant maximum, some five, or according to Doelter's idea, twenty or twenty-five degrees below the fusion point. According to Tammann, however, the velocity is really greatest at or close to the fusion point and the power of crystallization would be greatest were it not for the heat given at the latent heat of fusion, which raises the temperature and thus checks the action. If this heat could in some way be conducted away then the viscosity would steadily increase and the velocity of crystallization decrease continually below the temperature of saturation.

This velocity of growth must depend upon the rate at which molecules can be drawn in, and this in turn must be diminished by the viscosity,—the internal friction of a fluid. The viscosity of a fluid is, indeed, measured in just this way, by the velocity with which steel balls will move through it drawn down by the attraction of gravity.

We may look at it another way. The temperature of a body depends on the mean velocity of its molecules. As the temperature falls a smaller and smaller number of molecules then will in a given time pass on their paths within the range of a growing crystal where they will be added to it. Tammann's experiments[5] show that the crystals formed while the solution was only one degree to five degrees below the saturation or fusion temperature were larger and less elongate, and bounded by more different crystal forms so as to give on the whole more nearly equal dimensions; that from five to thirty degrees beneath the melting point they become more prismatic and are more regularly arranged with reference to the direction of growth and cooling. At lower temperatures yet, they tend to enclose glass and become forked. This has a direct importance to us for we may infer regarding the augite patches in the ophitic texture that since they are so equant in form they were formed before the magma fell much below the crystallizing temperature and therefore in a very limited range, while on the other hand the extremely microlitic forms of some feldspar crystals near the margin suggest at once that there was a considerable undercooling of the magma before they were formed.

The crystallization of any molten rocks or solution is due to a change in conditions. In the igneous rocks, as the name implies, loss of heat is the important factor. But as we have said it is not the only one. Change of pressure is another. Loss of some ingredient promoting fluidity like the evaporation of water from solution is another. Such an ingredient is known as a mineralizer.

We may remember the three factors as T. M. P., not temperature alone, but temperature, mineralizers and pressure. When we wish to emphasize the conjoint effect of the first two factors we speak of aqueo-igneous fusion.

The effect of loss of pressure may be greatest by indirectly promoting the loss of mineralizing gases.

It may be proved experimentally and theoretically that the slower the loss the coarser the grain, and in particular the slower the cooling the coarser the grain. And it may also be shown that the less the drop, that is the less the difference in conditions between those of crystallization and those of the country rock toward which the molten mass is cooling, the slower the cooling and hence other things being equal the nearer the country rock is to melting the coarser the grain. Examples of slow or slight change of conditions and coarse grain are rock candy and rock veins. Pegmatite must be another. Agate cavities have walls lined with relatively rapidly precipitated silica. Often at the center is quartz in larger crystals, more slowly formed as the supply became slower and slower.

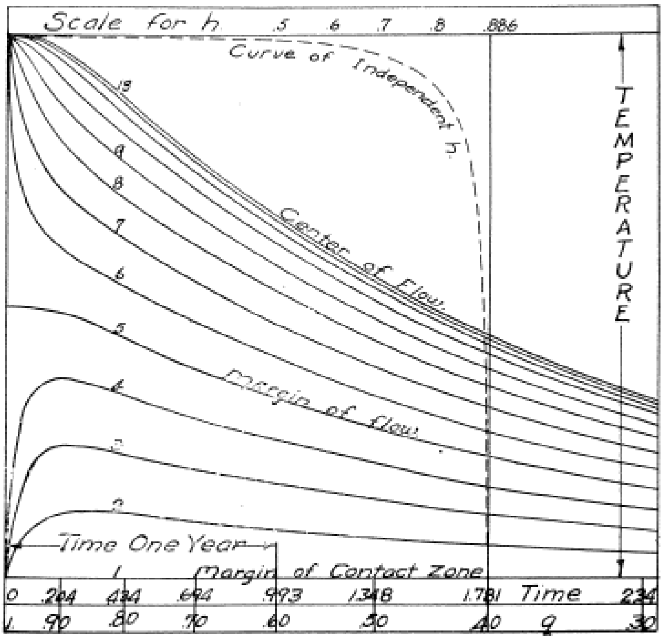

Figure 18. Curve showing cooling of lava sheet and heating of a contact zone supposed to be one-fourth the breadth of the lava sheet on either side. The abscissa (x) represents the time, the lapse of which is measured from left to right. The temperature for different times is given by a series of curves for a number of points equally spaced from the center of the flow to the margin of the contact zone which is supposed not to be heated at all. It will be noticed that outside the curve for the margin where the temperature begins half way between the initial temperature of the contact zone (which is taken as zero) and the initial temperature of the lava sheet, the curves first rise (as the contact zone heats up) and afterward fall. The diffusivity is supposed to be constant and in getting the scale of time from the curves found as functions of (q) the total breadth (c) was assumed as 100 feet and the diffusivity (a^2) as 400. These curves may be considered as contours of a surface which would represent the connection between temperature (v) time (t) and position (x). There is also given in dots a curve representing the variation of h (see text) with the temperature for early times when it is independent of the time.

Diffusion and loss of gases or mineralizers follow laws like those which apply to the loss of heat. The fundamental principle is that if there is at a given point a change of state (for instance, loss of temperature) in time there must be not merely a steady flow, as much transmitted as received, but an accelerated flow or change in space, the amount transmitted being increased over that received by the amount lost.[6]

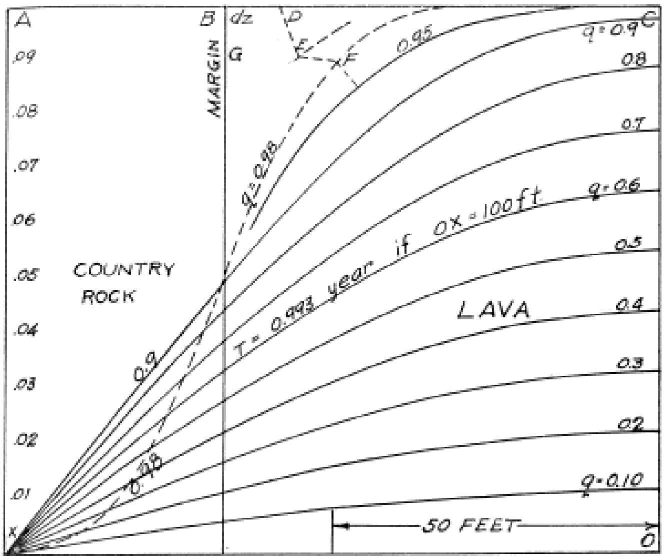

Figure 19. Shows the cooling of the same igneous sheet as Figure 18 with the temperatures as ordinates but the distance as abscissa, the curves being given for different epochs of time not equally spaced. It may thus be considered as a view of the same surface as Figure 18 looked at from the right hand side. There are also lines showing the effect of varying diffusivity. See text.

The general principles have been better expressed by Wright in the report for 1908 than I can phrase them.

The curves showing the temperature at any given time of an indefinite cooling sheet placed between two others which are allowed to heat up but kept at constant temperatures outside can be plotted without any serious difficulty if we suppose diffusivity to be constant. Such curves I have given among other places in the Isle Royale report (Vol. VI) and in the annual report for 1903 for three different widths of the outside sheets.[7] In this report I give a slightly different set showing the cooling in case the outside sheet, the belt supposed to be heated at the margin, is one-fourth of the total thickness of the hot sheet of rock and one-sixth of the total thickness supposed to be affected. To show the connection between the three variables, temperature (v), the position in the sheet and its distance from the margin (x) and the time (t) requires really a surface which may be represented by contour lines and in Figure 18 and Figure 19 I have given two views of the surface, one in which the abscissa is the time and the ordinate the temperature and the contour curves are equally spaced distances from the center of the flow. In the second figure the abscissa represents the distance from the center of the flow and the ordinate the temperature as before while the curves represent different, *not equally spaced* epochs in the cooling.

§ 4. CRITICISMS.

Now a perfectly fair criticism has been made upon my work by Doelter[8] and Harker,[9] viz., that I have considered in my work on the theory of the variation of coarseness of grain mainly the diffusion of heat, that I have assumed the diffusivity constant and have neglected the importance of such weighty factors as the undercooling and the effect of the giving out and absorption of latent heat which I have just mentioned. It will be found, however, that in my very first paper I noted the fact that the theory was incomplete and I have always found in practical applications that considerable corrections were due to other factors than those which had been mathematically treated and yet it is always necessary in any problem in physics to do just this,—to assume an ideal state of affairs much more simple than the real and then little by little as one finds variation in the real from the ideal to try to apply the necessary corrections. I have found in the augite of the lime melaphyres or ophites and in many other cases agreement enough with the numerical theory to make it of practical and, as I believe, scientific value.

As to the disturbing effect of undercooling and the latent heat given out in crystallization there are certain factors which may diminish its importance. One is that the rocks are composed of different minerals so that the effect is distributed at various temperatures. Another is that some of them crystallize quite slowly even when undercooled so that the giving forth of heat by the latent heat of crystallization is distributed. With regard to the very last mineral crystallized, the augite of the ophites say, a large portion of the rock may be already solidified and so only a very small quantity be crystallizing, the heat of which will be absorbed by the whole rock, thus diminishing and diluting its effect. The effect produced can be studied experimentally. Compare the curves of cooling plotted by Vogt.[10]

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[4] Tammann, G., Kristallisieren und Schmelzen, 1908, pp. 134, 140, 161.

[5] Kristallisieren und Schmelzen.

[6] In mathematical notation this statement becomes

$$du/dt=a^2\,d^2\text{—}u/dx^2$$

where a^2 is really a function of u and x and t but is generally taken as constant and called the diffusivity.

[7] In the curves figured by Queneau and copied unfortunately by Iddings the abscissas are not proportional to the time, but to a function thereof.

[8] Petrogenesis, p. 45.

[9] Natural History of the Igneous Rocks, pp. 219-221.

[10] Silikatschmelzlosungen, Pt. II, Pl. 1 and 4; Fig. IV. See also e. g. Fig. 12 of Day and Allen on the "Isomorphism and Thermal properties of the feldspar" showing the distribution of heat absorption in melting orthoclase.

§ 5. ALLOWANCE FOR VARYING DIFFUSIVITY.

As White has remarked, the effect of crystallization can largely be allowed for by assuming that the diffusivity is not constant. This we know is the case anyway. The diffusivity of a rock changes with the temperature. The change is ordinarily not very great during the important range except in case of crystallization. In this case it is and may be infinitely little. Now if we take the equation $du/dt=a^2 (d^2u/ (dz)^2)$ and assume a to be constant and compare it with another equation $du/dt=f(u) (d^2u/(dx))$ we can use the solution of the first for the second if we will take the successive values of x so that $f(u)/a^2=(dx)^2/(dz)^2$, that is to say, if we cut up the body into a series, of layers parallel to the margin each offering the same resistance to diffusion of heat. These will not be of equal thickness at different temperatures, nor will the total number in a given thickness of dike be constant. But suppose we try to find the connection between these layers and their thickness and the temperature and the position. For this purpose we may take the figure (19) in which curves for the equation with a constant diffusivity are shown with the distance from the center and the temperature (x and t) as abscissa and ordinate. Let this be the solution for z. At the initial temperature divide off the scale of x into a number of equal indefinitely small parts, BD=dx=dz, when u=v=1 and at this temperature they will all represent the same diffusivity and the same distance and the same width of successive layers offering the same resistance to the flow of heat. But as the temperature falls the diffusivity will change and if we connect each of the points at the top (e. g. D) with points like E representing the breadth of a layer having the same diffusivity as the initial layer (BD) the ordinate curves instead of being straight lines and parallel to the vertical axis will vary as DEF shown in the figure and will give us then the corresponding thickness.

If then we take our uz curves for the solution of

$$du/dt=a^2 (d^2u/du^2)$$

and for each point with a given temperature t shift the abscissa over as given by the zx curve we should have a series of curves to solve the equation $du/dt=f(u) (d^2u/dx^2)$ that would be fairly satisfactory, did we but know f(u) and were that fairly uniform, *but for the fact that in solving* $du/dt=a^2d^2u/dz^2$ *and getting these curves we have to use auxiliary equations which involve the scale of x and if we suppose it to vary we suppose also to vary therewith the breadth of the dike and its contact*. It is only then in initial cooling where the breadth of the dike is not important and no other factor involving linear dimensions but x and a comes in that this method could be used. We have been using practically a variable scale of distance and thickness that implies that the thickness and width of the igneous mass and contact zone will be variable from time to time and temperature to temperature. This method of solution, therefore, is not sound and can only be looked to in early cooling (and linear increase of grain) for cases in which the size of the mass or contact is of little importance, that is for crystallization which takes place before the center has cooled. Moreover, we know very little about the diffusivity as a function of u. At present and for this report all we need is to note that the tendency of decreased diffusivity is to crowd the curves of Fig. 19 into the corner B and that if augite (the last mineral consolidated) increases in grain clear to the center, much of the crystallization must have taken place in this early time.

The mathematical investigation is therefore of real importance, but may be skipped over lightly by those not especially interested so that they may come to the conclusions, at the end of the chapter.

§ 6. MATHEMATICAL TREATMENT.

GENERAL FORMULAE FOR ROCK GRAIN.

MARGINAL TEMPERATURE FIXED.

In an injected sheet of uniform temperature and diffusivity whose walls are kept at a fixed temperature the temperature may be expressed in two kinds of series, one of definite integrals of the probability integral type, the other the ordinary Fourier series terms; the former most applicable at the early stages of cooling, the latter in the later stages of cooling.[1]

Curves showing the manner of cooling, at first fast at the margin and slow at the center, then later slow at the margin and faster at the center are given in Figure 20.

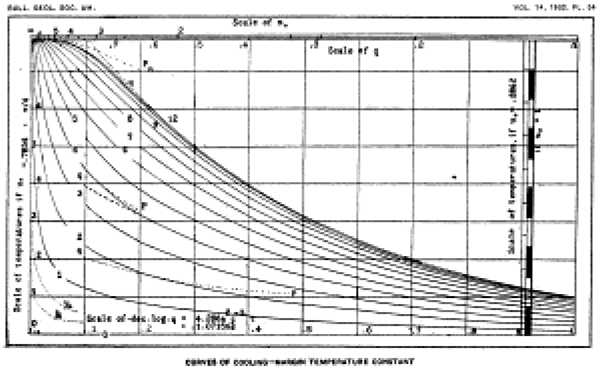

Figure 20. This shows the cooling of an igneous sheet, the margins of which are kept at a constant temperature, taken as 0° and represented by the bottom line of the diagram. The temperatures are represented by ordinates, and three different scales of temperature are given, corresponding to different values of the initial temperature. The main scale at the left is the same as used in the Isle Royale report. To the right is the scale if, as is assumed by Queneau, u_0 = .8862, and also if the initial temperature of the igneous sheet (that is, its excess of temperature over the surrounding rock) is taken at 1. The abscissas to the right represent the lapse of time, the main scale at the bottom being proportional to dec. log. *q* and *t*, and the scales above being proportional to m_0 and *q*, which are defined in the text. Curves for twelve equidistant points from center to margin are in full lines, and in dotted lines two curves still closer to the margin, one twenty-fourth and one forty-eighth of the distance to the center respectively. Also for curves 12, 4, and 2 we indicate by dashes the points where the curves of approximate solutions (obtained by using the first terms only of

equations 1 and 2) leave the curve which we have taken them to represent. This shows the error which we make in using such approximations.

$$(1)\quad \frac{u}{u_0} = P_m - \left(P_{m_0+m} - P_{m_0-m}\right) + \left(P_{2m_0+m} - P_{2m_0-m}\right) - - -$$

$$(2)\quad \frac{\pi}{4}\frac{u}{u_0} = q \sin \pi x/c + \frac{q^9}{3} \sin 3\pi x/c + \frac{q^{25}}{5} \sin 5\pi x/c - - -$$

where:

u is the temperature after a certain time (t);
u_0 is the initial temperature;
t is the time from the beginning of cooling;
x is the distance from the margin;
c is the thickness of the flow;
a^2 is the diffusivity,
$m = x/2a\sqrt{t} = x\, m_0/c$
$m_0 = c/2a\sqrt{t} = c\, m/x$
$\text{nat}\log q = -\pi^2 a^2 c^{-2} t = (\pi/2m_0)^2$
$P_m = \frac{2}{\sqrt{\pi}} \int_0^m -m^2 dm$ is the probability integral of which there are numerous tables. The report for 1903 and Johnson's "Theory of Errors" contain them.
$\pi = 22/7 = 3{,}1416$

Formula (1) is the Woodward-Queneau formula and converges most rapidly at early times and near the margin when m_0 is greatest.

Pm varies but little from 1 if m is much over 2, and for the center cooling that means if $m_0 > 4$.

Formula (2), which I used in the Isle Royale report[2], converges much more rapidly for large values of t the time or q. When formula (1) ceases to give a result approximate to the third decimal place, a couple of terms of formula (2) will usually give it. The linear grain will be expressed by the formula (where k depends on the power of crystallization of the mineral under the given conditions and will be *assumed* independent of the temperature and time, except as later provided):

$$(3)\quad g = k\sqrt{\frac{dt}{du}}\ .$$

For ordinary igneous magmas where probably according to Doelter du is often not over 40° and u_0 and u are to be reckoned in hundreds of degrees dt and du may be treated by the infinitesimal calculus or that of finite differences.

In any table of the values of u in the terms of x and t, such as are given in the report for 1903, we find the ratio dt: du as the quotient of the corresponding consecutive differences of argument and functions respectively, for the same value of x.

We deal with the partial derivative of t relative to u, x being supposed constant, that is.

A glance at equation (2) shows, what is not so clear in (1), that it is only the ratios u / u_0, x / c and a / c which are involved in determining t, moreover our tables are not constructed directly with t as an argument, though u / u_0 is the function. I found it convenient to express (3) otherwise and introduce instead of t a variable h (and m) where

$$(4)\quad h = \sqrt{\frac{-d\,(m)/m^2}{-d\,(u/u_0)/(u/u_0)^2}}$$

Then (3) may be written[4]

$$(5)\quad g = \frac{c\ k}{a\sqrt{u_0}} \cdot \frac{x}{c} \cdot \frac{1}{h\sqrt{2}\,(u/u_0)^2}$$

The advantage of doing this is that h proves to be a rather peculiar function of u, x and t, in that it is for quite a range of temperatures close to $.8863 = \sqrt{\frac{\pi}{4}}$, for a wider range is $\frac{u/u_0}{m}$ and, especially for early times before the center has cooled when u/u_0 is practically P_m, is independent of x, and its values are given by the following table, corrected from that in the report for 1903 in which a line unfortunately slipped out.

VALUES OF h BEFORE CENTER HAS COOLED.

$P_m = u/u_0$	m	$h = \sqrt{\frac{m^2 D_m u/u_0}{(u/u_0)^2}}$
0	0	$\sqrt{\pi}/4$
.1125	.1	.8863
.2227	.2	.88
.3286	.3	.88
.4284	.4	.88
.5205	.5	.88
.6039	.6	.87
.6778	.7	.87
.7421	.8	.86
.7968	.9	.85
.8427	1.0	.83
.8802	1.1	.80
.9103	1.2	.78
.9340	1.3	.75
.9523	1.4	.70
.9661	1.5	.67
.9763	1.6	.64
.9838	1.7	.55
.9891	1.8	.49
.9928	1.9	.45
.9953	2.0	.39
1.0000	infinity	.00

In Fig. 18, a curve is drawn giving h when it is a function of u/u_0 only (for early times) by the aid of which curves of relative coarseness of grain may be obtained readily for various positions and temperatures up to the time where the temperature at the center drops off.

The curves of grain are best located by their tangents and values at critical points.

At the margin

$$(6)\quad g = C'x \text{ where } C' = \frac{k}{a\sqrt{u_0}} \cdot \frac{1}{h}\ \frac{1}{\sqrt{2}\,(u/u^0)^2}$$

and C' is the rate of increase at the margin,—something that may be observed.

The grain at the center (E) we most readily find from equation (2). If there is a belt of uniform grain, (as I remarked in the Isle Royale report) $D_t \frac{u}{u_0}$ is a function of u not varying with varying x. This can be only if in (2) the expansion for $\frac{u}{u_0}$ is practically confined to the first term. For the differentiation of (2) gives

$$(7)\quad \frac{\pi}{4u_0} D_t u = \sin \pi x/c\ (D_t q = -\pi^2 a^2 c^{-2} q)\ - - -$$

$= -\pi^2 a^2 c^{-2}\ \pi/4\ u/u_0$ if terms after the first are neglected.

This will be the same for a given value of u regardless of x, and from (3) we find — writing E for g and substituting (7)

$$(8)\quad E = \frac{c\,k}{a\sqrt{u_0}} \cdot \frac{1}{\pi\sqrt{u/u_0}} = \frac{c\,k}{a\,\pi\sqrt{u}}$$

E then should really vary between the value of g derived from Eq. 6 if the increase kept up to the center, that is $\frac{C'c}{2} = \frac{c\,k}{2a\sqrt{u_0}} \cdot \frac{1}{h} \cdot \frac{1}{\sqrt{2}\,(u/u_0)^2}$ and the value just found in (8) which does not depend upon the initial temperature u_0. The ratio of these two is also the ratio of the distance from the margin at which the grain would be equal to that at the center if the marginal increase kept up (which we may call the belt of marginal increase) to the distance from the margin to the center. It is

$(9)\quad \frac{E}{C'c/2} = \frac{h\sqrt{2}}{\pi\, u_0/u}$ = about .4 to .5 of u/u_0 when the width of the contact zone is inappreciable.

Cf. Figure 21 below,

MARGINAL TEMPERATURE NOT FIXED.

When we come to consider the case that the sheet is supposed to have heated a contact zone, a formula which we found in the Isle Royale report enables us readily to construct the curves of decreasing temperature, which are shown in Figures 18 and 19.

This formula is as follows:—If v represents the temperature at a time t of a point at a distance of z from the center of a sheet the thickness of which is 2w with a contact zone of breadth y on either side, so that the whole zone affected or c is equal to 2w+2y. then—

$$(13)\ v = 1/2\ (u_{w+z} + u_{w-z})$$

where u_{w+z} is the temperature which would exist at the same time t after the beginning of cooling and conditions otherwise the same (except that its margins are kept at a constant temperature) in a sheet whose thickness was equal to c at a distance of w+z from the margin and u_{w-z} is the temperature at a point at a distance of (w-z) from the margin in the same sheet. Or if (w-z) becomes negative—that is, the point lies in the contact zone—we must assume

$$(14)\ u_{w-z} = —u_{z-w}\ \text{(in the contact)}$$

Now if we let x' be the distance of the point in the sheet with a contact zone from the margin of the sheet—that is $x' = {}^{c}/_{2} — z — w$

$$(15)\ v = 1/2\ (ux' + 2y + ux')$$

Thus we can obtain the curves of these figures either graphically (very rapidly) or by taking means of appropriate rows of the table of solutions of the case where the margin is kept at a fixed temperature, a table which is given in the Isle Royale report for an initial temperature of .7854, and in the report of 1903 for the initial temperature of 1.

Thus expressing the grain of the sheet with a contact zone y on each side as a certain function g ( ) of x' measured from the outside of the contact zone, of v the temperature of crystallization of u_0 temperature of injection, of y the width of the contact zone and of k, which may represent such factors supposed to be invariant as diffusivity and power of crystallization, we may proceed to locate curves of relative coarseness of the grain by their values and tangents (rates of change) at certain important points.

AT THE CENTER.

Here

(10) $v = u_w$ whence we have

(11) Center grain

$g\ (k,\ x' — c/2,\ v,\ u_0,\ y,\ c) = g\ (k,\ x — w,\ u_w,\ u_0,\ y = o,\ c.)\backslash$

The expression for the grain at the center will be, then, like Eq. 3.

If the cooling has gone on so far that there is a belt of constant grain at the middle ($m_0 < 2.5$ practically) then by Eq. (8).

$$(12)\quad g\ (k,\ x = \frac{c}{2}\ \text{or}\ x' = w,\ u,\ u_0,\ y,\ c) = E = \frac{ck}{a\sqrt{u_0}\ \pi\ \sqrt{u/u_0}} = \frac{ck}{a\pi\sqrt{u}}$$

The grain does not depend on the initial temperature, only on the difference between the temperature of crystallization and that of the country rock, being greater the less this is.

AT THE MARGIN.

(*Consolidation temperature nearer that of country rock.*)

Here.

(13) $v = 1/2u_{2y}$ whence we find that the grain at margin, if $u < u_0/2$ is,

(14) $g\ (k,\ x = y\ ,\ v,\ u_0,\ y,\ c) = \sqrt{2}\ g\ (k,\ 2y,\ 2v,\ u_0,\ o,\ c)$.

If u/u_0 is so low that this value falls in the second period, i. e., $m_0 < 2.5$, and the grain is that of the belt of central grain as in (12)

$$(15)\quad g\ (k,\ x' = y,\ v,\ u_0,\ y,\ c) = \frac{k\,c}{a\sqrt{u_0}} \cdot \frac{1}{\pi\sqrt{v/u_0}}$$

Comparing equation (14) and (15) with (11) and (12) we infer that if the temperature of consolidation is low enough the grain may be the same from center to margin. Otherwise it may be shown to be coarser at the margin if $u < u_0/2$.

Plate VI. Typical ophitic drill cores. Photographic plate after Annual Report for 1904, Plate XVII.

The cores are arranged with that nearest the bottom at the extreme left, as follows: 20620, 20619, 20618, 20617. Depth in drill hole 250, 232, 202 and 172 feet. Distance from margin at 257 feet, 4, 13, 28, 43. Apparent grain 0.5 to 1, 1 to 2, 2 to

3, 3 to 4 mm. Thin sections 1.5 to .74, 2 to 1.34, 3 to 2.8, 4.5 mm. 20618 analyzed.

(*Consolidation temperature nearer that of injection.*)

Inasmuch as $v = 1/2\, u_{2y}$ at the margin, so long as u_{2y} has not dropped from u_0, v will be equal to $u_0/2$. During this time the cooling will be as though the temperature at the margin were fixed at 0. It will be the same as that of a sheet of constant marginal temperature (which is taken as 0) of which the initial temperature will be $u_0/2$ and u will be $v - \frac{u_0}{2}$. The expression of grain in terms of the ratio u/u_0 we must change accordingly.

$$(16) \quad g\,(k, x = x' + y, v, u_0, y, c) = g\,(k, x', v - \tfrac{u_0}{2}, \tfrac{u_0}{2}\, 0, 2w)$$, where 2w =c—2y and going back to equations (5) and (6) we find

$$(17) \quad g = \frac{k}{a\sqrt{u_0}}\; \frac{x' \qquad \sqrt{2}}{h'\sqrt{2\left(\frac{2u}{v_0} - 1\right)^3}} = C'x'$$

Where h' stands in the same relation to $\frac{x'}{2w} \cdot \frac{2v}{u_0} - 1$ as h to $\frac{x}{c}$ and $\frac{u}{u_0}$ i.e., h' is for points close to the margin crystallized in early times independent of $\frac{x'}{2w}$, (this will be true for the linear rate of increase of grain at the margin) and while it depends on $\frac{2v}{u_0} - 1$ it will vary only between .7 and .87 if $\frac{2v}{u_0} - 1$ is less than .966, i. e., $\frac{v}{u_0}$ is < .983. That is unless the crystallization is practically coincident with the consolidation h' is roughly constant, until the center has cooled appreciably.

$$(18) \quad h' = \sqrt{\frac{-d\,\frac{x'}{2a\sqrt{t}}}{d\left(\frac{2v}{u_0} - 1\right)} \left(\frac{\frac{2v}{u_0} - 1}{\frac{x'}{2a\sqrt{t}}}\right)^3}$$

$$= \frac{2w}{x'}\,(M_0)\,\sqrt{\frac{\left(\frac{2v}{u_0} - 1\right)^3}{d\,\frac{2v}{u_0} - 1}}$$

in which t as a function of $\frac{x'}{2w}$ and $\frac{2v}{u_0} - 1$ and $M_0 = \left(\frac{a}{2w}\sqrt{dt}\right)$ must be taken from a table like Table I, Report for 1903, using $\frac{x'}{2w}$ for the distance, $\frac{2v}{u_0} - 1$ for the temperature.

INTERMEDIATE ZONE.

The curve of cooling of the extreme margin thus indicated may become practically coincident with a curve of cooling of a sheet of reference with width c and fixed marginal temperature of 0. If that is so,

$$(19) \quad v = 1/2\, u_{2y} = u_{y'}$$

when 2y represents the distance from the margin of the point whose cooling is represented by the curve of cooling of the sheet of reference (Figure 20), with constant temperature at margin, with which the curve of cooling of the margin becomes coincident. If the cooling has gone so far that it can be represented by the first term of Eq. (2) we can see that Eq. (19) can be true and that

$$(20) \quad \frac{\pi}{4}\,\frac{v}{u_0} = \frac{1q}{2}\,\sin\frac{\pi\, 2y}{c} = q\,\sin\frac{\pi\, y'}{c}$$

gives us a simple trigometric equation to solve to find y'

$$(21) \quad \frac{\pi\, y'}{c} = \sin^{-1} \tfrac{1}{2} \sin\pi\,\frac{2y}{c}$$

But we also see that if y is so small, that is, the contact zone so small, that sin 2 π y' / c is proportional to 2 π y / c then y' will be the same proportional to y, and more generally, if it is so small that sin n π y / c is proportional to n π y / c, to the number of terms of Eq. (2) covered by n will y' be proportional to y and eq (19) be true. Not only that, but in equation (1) if $v/u_0 = P\,\frac{y'}{2a\sqrt{t}}$, and if $P\,\frac{2y'}{2a\sqrt{t}}$ is nearly proportional to $\frac{y'}{2a\sqrt{t}}$ which it is if $\frac{v}{u_0} < .33$, then to the same extent will:

$$(22) \quad \frac{v}{u_0} = \tfrac{1}{2}\,\frac{u_{2y}}{u^0} = \tfrac{1}{2}\,(\text{constant} \times)\,\frac{2y}{2a\sqrt{t}}$$

$$= (\text{constant} \times)\,\frac{y'}{2a\sqrt{t}}$$

and $v = u_y$

That is to say if the contact zone y is small enough so that 2 v = $u2_y$ becomes 0.33 u_0 before the center has cooled perceptibly, or the marginal temperature becomes say 1/6 of the initial, the cooling at that margin will be the same as at a corresponding point of the sheet of reference whose walls are kept cold. At the same time the cooling at the center is the same as that of another point in the reference sheet, at a distance $\frac{c}{2} - y$ from the wall. The cooling on two planes, center and margin being the same as on two planes of the reference sheet, the cooling between must be the same, except that due allowance must be made for the different distance apart of the two sets of planes. The distance of corresponding planes being thus proportional we obtain a formula:

$$(23) \quad g\,(k, x, v, u_0, y, c,) = g\,(k, \frac{c - 2y + y'}{c - 2y}\, x' + y', u, u_0, 0, c) = A\,x' + B$$ c\

if 2 sin y π c = sin 2 y π c nearly.

At the center (23) reduces to formula (11) and writing

g = Ax' + B and the expression $(k\,c/a\sqrt{u_0})\,K$ comparing it with Eq. (3), and (5) we find

$$(24) \quad A = \frac{K}{c}\,\frac{c\text{-}2y\text{-}2y'}{c\text{-}2y} \cdot \frac{1}{h\sqrt{2\,(u/u_0)^3}}$$

$$(25) \quad B = K\,\frac{y'}{c} \cdot \frac{1}{h\sqrt{2\,(u/u_0)^3}}$$

The equation (23) is the equation of another tangent to the curve of grain if we consider A and B constant. It will appear in the case of small contact zones at a point of minimum curvature.

It is of importance as the rate of increase A is most characteristic of the Keweenawan flows. It becomes more and more important, and represents more and more of the curve of grain, the less the contact zones are and the more immediate the crystallization.

It may be distinguished from the other tangent to the curve of grain by the fact that it does not give a 0 grain at the margin. We notice, too, that

$$(26) \quad \frac{B}{A} = y' \cdot \frac{c\text{-}2y}{c\text{-}2y\text{-}2y'} = y'\,\frac{2w}{2w\text{-}2y'} = y' \cdot \frac{w}{w\text{-}y'}$$

This is always positive unless y + y' > 1/2, i. e., unless the contact zone is greater than the width of the dike > c/4 on each side, and is for small contact zones practically proportional to the contact zone.

If a series of observations of grain give a value of B negative or very small it is pretty likely that they refer to the equation y = C' x' and that the value of B is due to the errors of observation.

APPROXIMATE FORMULAE.

If we make certain simplifications, which can generally be done without appreciable loss of accuracy, we can obtain formulae not bad to handle numerically.

Assume that y is equal to y' and that the fraction $\frac{c-(2y+y')}{c-2y} = 1$. This we may do when the contact zone is relatively small. We will also introduce h' as before and call $v/u_0 = f^2$ and we have the following formulae:

(27). $C' = K/ch'(2v/u_0 - 1)^{\frac{2}{3}} = K/ch'(2f^2 - 1)^{\frac{2}{3}}$. As $K/c = k/a\sqrt{u_0}$, C' is independent of the size of the dike or the contact zone, and is the marginal rate of increase.

(28) $A = K/ch(v/u_0)^{\frac{3}{2}}\sqrt{2} = K/chf^3\sqrt{2}$, from (24).

(29) $B = Ky'/ch(v/u_0)^{\frac{3}{2}}\sqrt{2} = Ky'/chf^3\sqrt{2}$, from (25).

(30) $E = K/\pi\sqrt{v/u_0} = K/\pi f$, and is independent of initial temperature.

From (28) and (29) we can determine y', the effective contact zone, which is B/A.

(31) $y' = \frac{B}{A}$.

If y comes out less than 1/12 of c, we may be sure that so far as the contact zone is concerned our approximate solutions are close. From (28) and (30) we can find c in the terms of A, E and K—that is, we can sometimes by observation of the grain determine the thickness of the dike before it was completely penetrated if from a general knowledge, or from Eq. 30 we could infer f. Moreover, we can find f in the terms of A, E and c, and if f^2 does not come too near to unity we may feel that our approximate formulæ and results from them are not likely to be far out. We can also find K in the terms of A, E and c, or if we have also Eq. (27) we can either check on our observations or get along without c or some other factor. From formulæ (27) and (28) we can find f in the terms of C' and A, although the equation is a cubic. It is quite rapidly solved by approximation. We can then find K/c.

Then let a certain observed rate of increase of grain, represented by the slope of a certain straight line tangent to the curve of grain be s. We may not know whether it represents C or A as we have said. We shall have either $f^2 = u/u_0 = E/.45\ hsc$ — from equations (30) and (28) letting s = A; or from equations (30) and (27) letting s = C'

(32) $2f^2 - 1 + (E/.45\ h'sc)^{\frac{2}{3}}(2f^2)^{\frac{1}{3}}$. This equation is solved approximately in Figure 21. Thus it will be comparatively easy to obtain the alternative values of v/u_0 on the two hypotheses. Since $2v/u_0$ is always between 1 and 2 and the cube root varies but slowly, it will be easy to insert an approximate value in (46) and obtain nearer approximations. Moreover having found v/u_0 we can go on to find K.

(33) $K = \pi E/f = \pi E\sqrt{\frac{u}{u_0}} = Cch'(2f^2 - 1)^{\frac{2}{3}} = Ach\ f^3\sqrt{2}$.

In formulae 24 and 28, in the expression for A, as v approaches u_0, h will approach zero and so the expression for A might become infinite. That would imply that the nearer the initial temperature is to the temperature of a consolidation the greater will the gradient A become but of course this is limited by the fact that at a temperature very close to that of a consolidation the lava flow would be so viscous as no more to flow. The temperature above the consolidation point at which the magma becomes sharply fluid is very much less for magmas and glasses containing lime than for those which contain soda and therefore a coarser and better marked rate of increase and a more distinct development of the A gradient is noted in the lime melaphyres. At the same time there is distinct signs of a limit here, and the A gradient is, so far as I know, never over one millimetre in seven feet. From this we can draw an inference regarding the temperature at which a lava is fluid enough to flow compared with that of the formation of augite.

An interesting question is where the various tangents meet—that is, where will the zone of marginal grain become equal to that of the center. If we refer to the equations of the three tangents we have the following formulæ:

(34) $x'_{13} = E/C' = ch'(2f^2 - 1)^{\frac{2}{3}} / \pi f$,

where x'_{13} is the abcissa of the meeting point of tangents representing the rate of increase of grain at the extreme margin C', and that at the center.

The solution of this approximate formula as well as (in dots) curves representing more accurately the actual relation for three different breadths of contact in terms of $x'_{15} / c = E / C'c$ is given by the full line of Figure 21 (Fig. 6 of the, annual report for 1903) repeated here for these values.

u / u_0	.84	.80	.76	.71	.66	.61	.56	.50
$E / c'c$	.168	.145	.121	.093	.067	.038	.014	0

If instead of expressing the ratio of superfusion as a function of the marginal rate of increase C' the grain at the center E and the total width affected it be expressed in terms of the distance from margin W we may roughly express the relations in words by saying that E, the grain at the center, is less than that which would be found if the increase at the margin, kept up proportionately to the superfusion, and the drop from the initial temperature to that of crystallization is to the initial temperature (reckoned from that of the country rock as zero), as the thickness of the central belt in which the coarseness would be about as much as at the center is to (somewhere between once and twice) the total thickness.

(35) $\frac{u_0 - u}{u_0} = \frac{2w - 2E/C'}{2w(\times 1 \text{ or } 2)}$

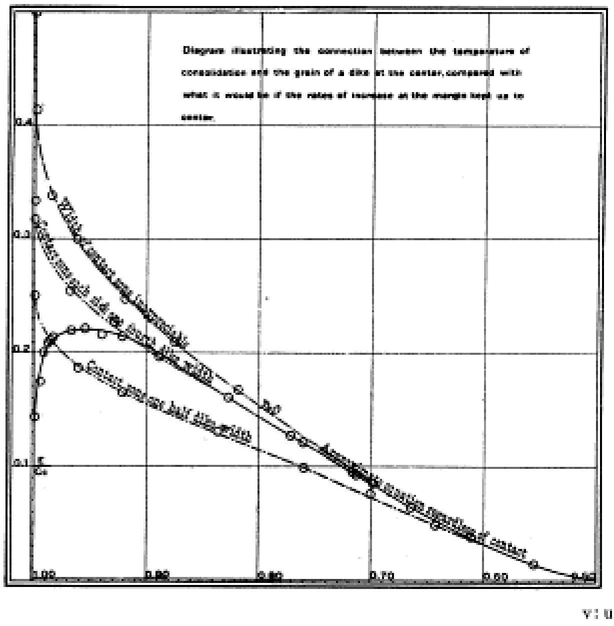

Figure 21. S shows E / C'c, or the ratio of the grain at, the center to that which would be reached if the rate of increase at the margin kept up for a distance equivalent to the whole zone affected. The full curve is the approximate solution given by equation 34 of the text. The dotted curves were computed for particular widths of the contact zone as shown thereon.

Similarly

$$(36)\quad x'_{23} = (E—B) / A = .45\ hcf^2 — y',$$

where $(x'_{23} + y') / c$ is less than .4; and finally equations (27), (28), and (29) will determine a point

$$(37)\quad x'_{12} = B / (C' - A) - y \Big/ \frac{h}{2h'} \left(1 - \frac{1}{2f^2}\right)^{-\frac{1}{2}} - 1,$$

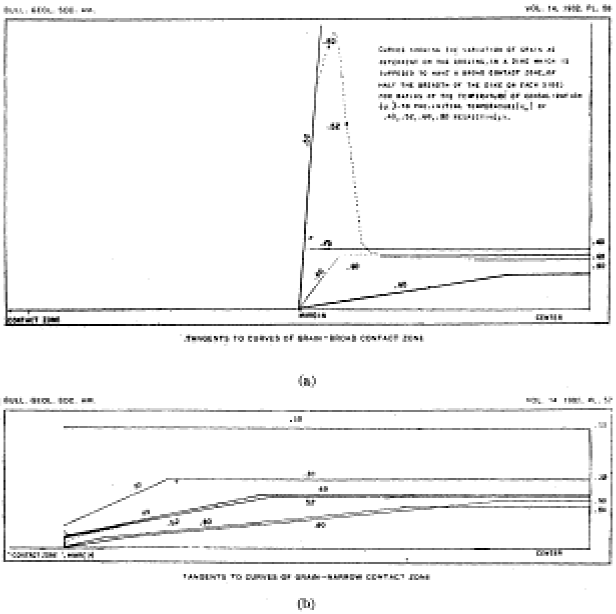

Figure 22. Illustrates the variation of coarseness of grain from the margin to the left to the center at the right in flows, intrusive dikes or sills which have either: (a) a broad contact zone; or (b) a narrow contact zone in which the contact zone heats up and cools down quickly. The curves are dotted in. Important tangents to them are drawn in full lines. The decimal figures adjacent to each curve indicate the ratio of the temperature of consolidation to that of initial injection or intrusion, the temperature of the country rock being taken at zero.

From formulæ (35) and (36) we shall not be able to find the width of the contact zone, but we may if we know over what range some of these formulae are closely applicable. If, for instance, formula (27) holds at least to a value x', it may be shown that

$$2y \text{ is not less than } x' / P^{-1}\,[2(u / u_0)—1 \text{ or } 2w]$$

Also in equation (37), if we know exactly x'_{12}

$$(38)\quad y = \left(\frac{(2 \text{ to } \infty)^{\frac{1}{2}} h}{2h'} - 1\right) x'_{12} \quad = \left(1.4 \text{ to } \infty\ \frac{h}{h'} - 1\right) x'_{12}$$

C’ must always be greater than A and between C' and A there is the relation

$$(39)\quad \frac{C'}{A} = \left(\frac{h\sqrt{2}\,(2 - 1/f^2)^{\frac{1}{2}}}{h'}\right) \left(\frac{C - 2y}{c - 2y - 2y'}\right)$$

up to values of $f^2 = u / u_0$ of about .80 $\frac{h}{h'}$ is nearly 1 but as u / u_0 gets above .90 it rapidly diminishes but does not fall below $\frac{1}{\sqrt{2}}$. Thus for small contact zones

$$(40)\quad \frac{C'}{A} = \frac{\sqrt{2}}{1 \text{ to } \sqrt{2}} \left(2 - \frac{1}{f^2}\right)^{-\frac{1}{2}}$$

Again as c — 2y = 2w we find $\frac{c - 2y}{c - 2y - 2y'} = \frac{2w}{2w - 2y'} = \frac{w}{w - y} = 1 \Big/ \left(1 - \frac{y'}{w}\right) y'$ so that if $y' = w\ \frac{C'}{A} = \infty$

Some of the tangents just described are shown in Fig. 22.

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[1] See Byerly, "Fourier's Series," articles 49-50; annual report for 1903, p. 210 (misprints corrected here); and A. L. Queneau, Am. Jour. Sci., 1902, p. 393.

[2] See Byerly, Fourier's Series, Article 60. ex. 1.

[4] The steps are somewhat more fully given in the report for 1903.

§ 7. APPLICATIONS.

If the initial temperature and diffusivity of igneous magma are not dependent on the position and time, whatever crystallization takes place at the margin before the center or margin has cooled appreciably follows the law that the coarseness of grain is proportional to the distance from the margin (the margin not varying in temperature either because kept at a constant temperature or, if it is the country rock, because it has not departed much from it, at a temperature half-way between the initial magma and country rock temperature).

On the other hand the crystallization that takes place after the center has cooled down considerably should be uniform in grain or not less than that at the center.

This belt of uniform grain will occur, if at all, near the center and, as we have said, the greater its width the nearer to the crystallization temperature must the marginal temperature have been. In this belt the size of the grain may not depend on the initial temperature at all but besides being proportional to the size of the dike and the power of crystallization, and inversely proportional to the square root of the diffusivity, will be the greater the less the difference between the crystallization temperature and the temperature of the country rock down to which cooling is taking place.

If the temperature or other conditions of crystallization are nearer those of the country rock than those of the magma, there may be no marginal zone of finer grain.

There may be a belt of coarser grain than that at the center. It should be at the margin if the initial marginal temperature is just above that of consolidation. The higher the temperature of consolidation the farther in and less defined the belt must be if present at all. To be at all appreciable it must be close to the contact. It is produced as the contact zone approaches the maximum temperature it attains. The fact that the grain of a rock may be coarser at the margin than at the center, considering loss of heat alone as a factor in crystallization, is not easy to see at first glance. It means that the margin cools more slowly *not at the same time*, for of course it cools first, but at or through the same range of temperatures. This may be made more clear by looking at a figure of cooling with a broad contact zone (Fig. 18). We see that the curve of cooling at the margin takes about half a year to drop .1 in temperature, from .5 to .4 of the initial temperature, while the center, when it gets down to the same range, passes through it in not much more than a quarter year. We may make this slower cooling at a given temperature at the margin seem more reasonable by the following considerations.

The rapidity of cooling depends among other things on the amount of drop to be made. Now at the beginning the contact country rock is cool, the drop marked, and the cooling rapid; accordingly, for that part of the dike that cools and crystallizes during that time, the grain is fine. But as the country rock heats up, while it is heating up the interval down to which the dike of molten rock must cool is growing less and so the crystallization is very much slower, the grain much coarser than were the contact zone kept at a fixed temperature. Later the contact zone cools too, with the dike as a whole. Now while the contact zone is heating up and the dike cooling down the parts at the contact are held at a temperature just about half way between the initial temperature of the dike and the country rock. Thus the conditions are favorable for very slow crystallization in the part of the dike then crystallizing.

A uniform grain throughout like some of the dikes in the Mt. Bohemia oligoclase gabbro may then indicate one of three conditions. (1) An excessively hot magma. I have not seen any yet which seemed to me attributable to this cause. (2) The retention of some mineralizer which makes the crystallization point relatively low. This condition may hold not only in veins but in many aplitic and pegmatitic dikes. (3) The fact that the country rock itself was relatively near the fusion (respectively solution) point, as in the case of dikes injected into granites or gabbros which have only just consolidated.

Effusive rocks generally have broader marginal zones of grain increase than intrusives for (1) the magma is likely to be less hot, in fact to flow and keep stirred up until it stiffens near the crystallization point. (2) Loss of mineralizers is likely to raise the crystallization point. (3) The country rock is relatively cool and if wet will absorb a large amount of heat, making the thermal contact zone narrow. Marginal belts of coarser grain I have never observed.

As a matter of fact most of the Keweenawan ophitic melaphyres do show an increase of grain, especially of augite, from the margin to the center. The rate of increase, however, is not strictly proportional to the distance from the margin except for a short distance near the same. There is a narrow contact zone of a meter or less which heated up first, and a zone of corresponding width inside the dike in which the grain of the augite increases quite rapidly and proportionally to the distance from the margin (at the rate C’). Then later the contact zone and all cooled and for the part then consolidated the grain increase changes to a smaller rate (A) which is more nearly proportional to the distance from a point outside the exterior of the contact zone.

But the rapid marginal rate of increase is usually confined to the first few feet, and can be determined only by careful microscopic work. The rate of increase is, on the whole, more uniform in the lower part of each flow than the upper, where the amygdules and probably original eddies in the flow introduce uncertain factors.

My original empirical rule for the second rate of increase (A) was that in the commonest type of Keweenawan flow, the ophitic melaphyre with about 10 per cent of CaO composed of about 55 per cent labradorite and 30 per cent augite, the grain of the augite in millimetres was,, allowing a margin of 1 mm. each way, equal to 6 per cent of the distance in feet from a point 20 feet outside the margin, or at the rate of 1 inch in 400 feet (1 mm. in 16 feet). More scientifically expressed the ratio is 1 :4800 or .00021.

Further investigations indicate that the main rate (A) may be somewhat higher, up to .00046 (1 mm. in 8 feet) without being marginal. It must not be forgotten that this formula from eye observation is rough, covering really two different theoretical gradients.

However, the errors in measuring grain are of the same order, and there are also errors which come in front unequal original temperature and variation in composition, such as produce the variation from ophitic to doleritic texture.

PRACTICAL APPLICATIONS OF OBSERVATIONS OF AUGITE GRAIN IN OPHITES.

1. Amygdaloid inclusions, bombs, or streaks and doleritic streaks in the body of a flow may be distinguished from the main amygdaloid top by the more regular and persistent diminution of grain toward the latter.

2. The extra coarse flows are extra thick and extra persistent and may be identified by the maximum grain. For instance, the "Greenstone" just above the Allouez conglomerate extends from Keweenaw Point to Isle Royale and down the point to Portage Lake, though it thins in this latter direction. The augite mottles are as large as 3 inches across where it is thick. T he Mabb ophite with a grain of over 7 mm. comes shortly above the Baltic lode. One may thus identify a flow as a unit.

3. One may, from an extra slow' increase of grain in diamond drill holes, infer that the bed is being traversed obliquely. One must have due regard to the possibility of being deceived by a different rate of increase of grain due to some other cause,—different chemical composition, for instance.

But if the same bed is cut by different holes traversing it at different angles[5] one can often feel fairly safe. For instance, Hole 5 at the Challenge exploration (Chapter V, § 18) was put down through a heavy glacial overburden 143 feet where little or nothing was known as to the dip. The slow increase of ophitic mottling in the bed from 143 to 257 feet led Dr. Hubbard quite correctly to infer that it was traversed quite obliquely and had a dip of 60° or more. (See Pl. XVII, report for 1904, Pl. VI, and Fig. 59 of this report). Another illustration is Empire section, Figure 24, Hole 5, Belt 51.

4. If a variation in grain can be noted on two sides of a shaft, a cross-cut, or an outcrop, the direction of finer

grain is probably that of the nearer amygdaloid or conglomerate, and the coarseness of grain will indicate the probable distance.

This is of especial use in a drift covered country where it is often impossible to sink exactly on the amygdaloid ashbed. Thin principle was used in fixing the position of the Allouez in the Empire section. (Fig. 24.)

Good illustrations of the importance of grain in determining dip will also be found in the southern part of the Mandan section, where I was led to infer a steep dip from observations in vertical holes before it was otherwise proved.

5. A sudden variation in grain in crossing a seam may indicate a displacement and guide one in determining its character and amount. (Cf. the Isle Royale section, drill hole 10 and the Challenge exploration.)

6. It will often be possible to tell how far there is yet to go to traverse a bed after it has been more than half penetrated, for it will begin to get finer again.

In this way it was possible to say that a Calumet and Hecla drill hole near Shaft 21 which was stopped by an accident was just about 30 feet from its goal.

7. A uniformity and system in grain may distinguish small outcrops from large boulders. This principle and principle 4 were also made use of near Shaft 21, Calumet and Hecla, where there were some dubious outcrops of the hanging of the Kearsarge lode.

8. Conversely, a very coarse grain indicates a very heavy bed of trap, and thus gaps in a geological section may be filled. It does not, for instance, require continuous trenching or exposure by drilling over the Greenstone to make sure of not missing amygdaloids.

9. Large masses (30 feet or more) of aphanitic (porcellanic) rocks, if igneous, are likely to be felsitic.

10. Intruisives are often characterized by extra coarse feldspar, and relatively narrow marginal bands of finer grain near the margin.

11. Beds without variation of texture (or actually coarser) at or near the margin are intrusive.

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[5] See Bed 32 of the Clark-Montreal section.

THE GREAT SEAL OF THE STATE OF MICHIGAN
A.D. MDCCCXXXV