

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 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 much finer grained than the augite. With the exception of these few effusives,<sup>28</sup> 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,<sup>29</sup> Lane, Winchell and Grant, and numerous other writers since Wadsworth and Wichmann 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*.<sup>30</sup> The *quartz diabase* is in no sense analogous to Diller's *quartz basalt*, where the quartz is in the form of corroded brotocrysts. *Enstelite* 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 due 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

<sup>28</sup>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.

<sup>29</sup>Minnesota Geological Survey, Bull. No. 8, 1893; Canada Survey, T. CC. 1886, 3P 1890; Canadian Inst: Proc. 5, 1886, p. 177-183; Am. Geologist Vol. I, 1886; pp. 199-211; Am. Geol. Vol. VII, pp. 153-164.

<sup>30</sup>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*?

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<sup>31</sup> and by various Canadian writers. It is a Latinization of Irving's name *anorthite rock*. A. N. Winchell would replace it by the term *plagioclase* 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

<sup>31</sup>Minnesota Survey Bull. No. 8, 1893, pp. 1-23.

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.<sup>32</sup> It seems, therefore, that it would hardly be wise for me in a report in some sense final to change the names heretofore 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,<sup>33</sup> 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 cases give the amygdaloidal portion is a very uncertain factor. It is not usually over five feet. When greater thicknesses are

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

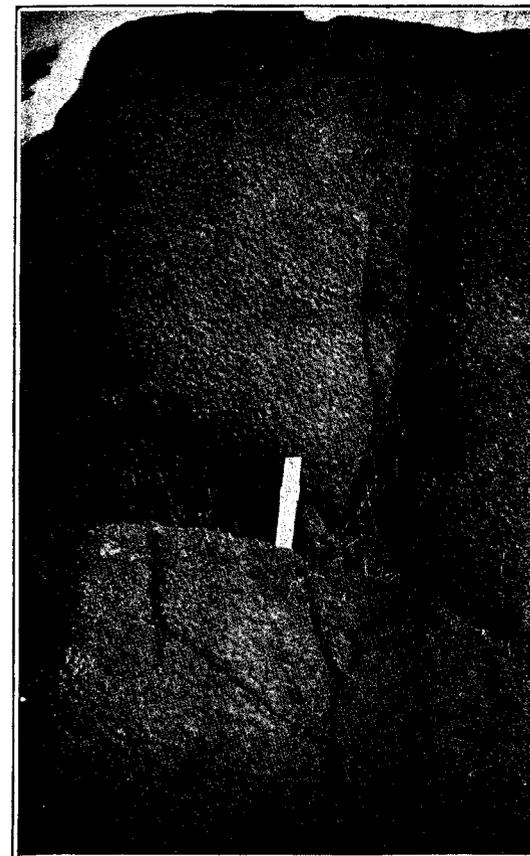
<sup>33</sup>Vol. VI, Pt. I, p. 235.

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 porphyry*. 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.

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*.<sup>34</sup> 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 crystal-

<sup>34</sup>Vol. VI, Pt. I, p. 167.



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 THE BULL. GEOL. SOC. AM., VOL. 18, 1906, PLATE 71. SEE ALSO REPORT FOR 1908.

lization, 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 crystallizing 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<sup>35</sup> is inclined to object to this. The question is discussed in the next chapter. The rocks are precisely those described by Pumpelly and Marvin who noticed the flashing due to the augite cleavages when the texture is sufficiently coarse and called them *luster mottled melaphyres*.

<sup>35</sup>Bull., Geol. Soc. Am., Vol. 20, p. 661. U. S. G. S. Monog. 52, p. 398.

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 prevailing 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 climatic significance of white mica in rocks of this nature.<sup>36</sup>

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 sometimes 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 *arroyos* 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 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

<sup>36</sup>Journal of Geology, 1908, p. 268.

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<sup>37</sup> 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

<sup>37</sup>N. Jahrbuch f. Min. 1869.

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 cross-cut 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.

SUMMARY OF KEWEENAW ROCKS ACCORDING TO QUANTITATIVE CLASSIFICATION.

I-1. 3. 1. 2. Magdeburgose. 1. 3. 2. 3. Tehamose. 1. 4. 1. 1. Lebachose.	Pigeon Point, Minn. Wadsworth, 1887. Quartz Diorite Pigeon Point, Minn. Bayley, 1889-95.	Melaphyre, Middle Bed 87 Eagle River section, Mich. Pumpelly, 1878. Porphyrite, Isle Royale, Mich.	II-5. 3. 5. Beerbachose. Porphyrite, Isle Royale, Mich. Lane, 1893-98.	III-1. 3. 4. Vaalose. Diabase granophy- litic, Cleveland Point, Mich. Lane, 1893-1898.	Van Hise, 1892. Gabbro (granular), Bashanauqua Lake, Minn. N. H. Winchell, 1893.
Felsite, Keweenaw Point, Michigan. Hubbard, 1898.	II-4. 3. 2. 4. Tonalose-dacose. "Red rock dike," Mt. Bohemia, Mich. Lane, 1905-06.	Lane, 1893-98. Orthoclase gabbro, Duluth, Minn. A. N. Winchell, 1900.	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.	III-5. 3. 4. Campionose. Melaphyre, Bottom of bed 87, Eagle River sec- tion, Keweenaw Point, Mich. Pumpelly, 1878. Orthoclase gabbro, Duluth, Minn. A. N. Winchell, 1900.	Olivine gabbro, Birch Lake, Minn. Gabbro, T. 46 N., R S W., Minn. Bayley, 1889-95. Troctolite, Duluth, Minn. A. N. Winchell, 1900.
I-1. 4. 1. 3. Liparose. 1. 4. 2. 3. Tuscanose. Granite, Soda Granite, Quartz Keratophyre, Pigeon Point, Minn. Bayley, 1889-95.	II-5. 1. 4. Umptekose. Felsite porphyrite, Keweenaw Point, Mich. Hubbard, 1898.	II-5. 3. 3. 5-4. Beerbachose Andose. Melaphyre porphyry, Duluth, Minn. Streng, 1877. Gabbro, Baptism River, Minn. Wadsworth, 1887.	II-5. 4. 4. 5. Atrvegnose. Melaphyre, Lower part bed 64, Eagle River section, Keweenaw Point, Mich. Pumpelly, 1878. Diabase, Sec. 13, T 47 N., R 46 W., Cochran Co., Mich.	Diabase, Light house Point, Mich. Ophite, St. Mary Mineral Land Co., Keweenaw Point, Mich. Ophite Mt. Bohemia, Mich. Lane, 1905-6.	
I-1. 5. 4. 4. 5. Labradorose. Plagioclase, Carlton Peak, Minn. A. N. Winchell, 1900.	II-5. 2. 4. Akerose. Porphyrite, Keweenaw Point, Michigan. Hubbard, 1898.	II-4-5. 3. 3. 5. Placerose Beerbachose. Quartz gabbro, Little Saganaga Lake, Minn. A. N. Winchell, 1900.	IV-1. 1. 1. 2. Cookose. Hypersthene gabbro, Gullfint Lake, Minn. Bayley, 1889-1895.		
II-4. 2. 3. Adamellose. Gabbro (?)	II-5. 3. 4. Andose. Homblende gabbro, Duluth, Minn. Streng, 1877.				

## § 4. METHODS OF STUDYING CHEMICAL RELATIONS.

41) *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<sup>35</sup> has recently determined according to this classification the position of all the Keweenaw 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 Keweenaw rocks.

## CORRELATION OF NOMENCLATURE OF KEWEENAW 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,  $3 : 5 > \text{Quartz} : \text{Feldspar} > 1 : 7$ .

Rang 1. "Peralkalic," "Liparase."  $K_2O + Na_2O > 7 \text{ CaO}$ .

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 gabbro aplite.

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, "Labradorose." CaO between 1.6 and 7 alkalis.

Subrang 3. Presodic, Labradorose,  $K_2O < 0.6 Na_2O$ , Winchell's Plagioclase or Lawson's Anorthosite.

<sup>35</sup>Journal of Geology, Vol. 16, No. 8, Dec. 1908, p. 765. U. S. G. S. Monog. 52, p. 395.

CLASS II. Dosalone and Dosalone quartz and feldspar  $> \frac{5}{8}$  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  $\text{Na}_2\text{O} > 5 : 3 \text{K}_2\text{O}$  or persodic  $> 7 \text{K}_2\text{O}$ .

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. Alkalic, 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, placeros—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,  $\text{Na}_2\text{O} > 5-3 \text{K}_2\text{O}$ .

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\*\*

also all of Order 5, i. e. Quartz 1 : 7 feldspar, all 4 dosodic or persodic.

Rang 3. Alkalic calcic.

Order 4. Vaalare quartz  $> 1-7$  but 3-5 feldspar.

Vaalase and *Vaalose* diabase granophyre, i. e. quartz diabase, Sharpless, 1892, p. 134.

\*\*A slight increase in alumina within limits of analytical error would bring it into Order 5 and perhaps into the Hessoses.

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. Permirlie.  $\text{CaO} + \text{MgO} + \text{FeO} > 7 \text{Na}_2\text{O}$ .

Section 1 Permirlie  $\text{MgO} + \text{FeO} > 7 \text{CaO}$ .

Subrang 2. Domagnetic.  $\text{MgO} : \text{FeO} < 7 > 5-3$ .

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<sup>40</sup> are not really "from the Keweenaw peninsula," but rather from the Keweenawan of Minnesota.<sup>41</sup>

Professor Osann's chemical classification is found in a series of papers.<sup>42</sup> 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

<sup>40</sup>Journal of Geology, Vol. 1, p. 712.

<sup>41</sup>Journal of Geology, Vol. XVI, p. 774.

<sup>42</sup>Tschermak's Mineralog. und petrographische Mittheilungen. XIX, XX, and XXI.

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 subrang. The dominant type of the Keweenaw basic rocks, which is also by far the most wide spread, is what Osann calls the Keweenaw 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

$$\text{is } s_{50.80} A_{2.45} C_{11.00} F_{22.21} a_{1.5} c_6 f_{12.5} n_{9.1}.$$

It is interesting to notice how closely this corresponds to the formula of the backbone of Keweenaw Point,—the Greenstone and the St. Mary's core ophite (Sp. 20618, Pl. VI) is not very far from the Keweenaw type, being  $s_{52.2} a_{2.3} c_{6.5} f_{11.13}$ . 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

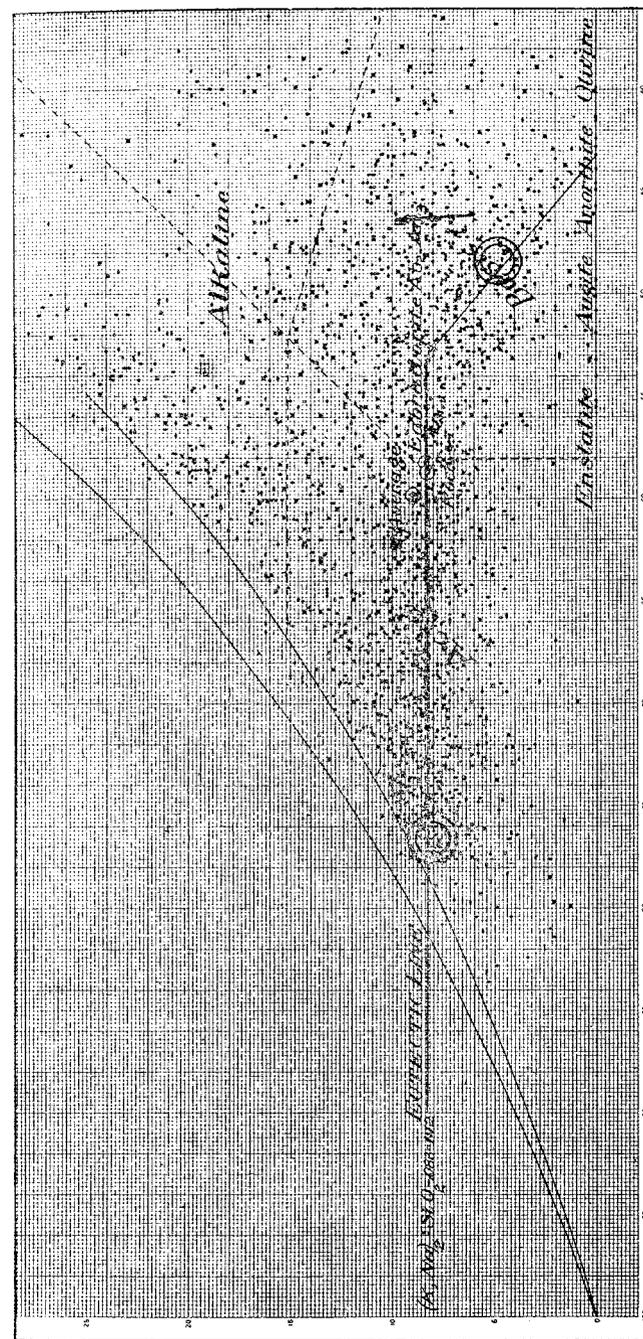


Fig. 12. Diagram 45 from Iddings. See also Jour. Geol. Vol. 12, page 91. The abscissa are percentages of silica running down to the right. The ordinates are the ratios of the molecules of alkali to the molecules of silica. Dots represent numerous analyses collected by Iddings. The double circles have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

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 Keweenaw rocks on Idding's plan is shown in Fig. 12.

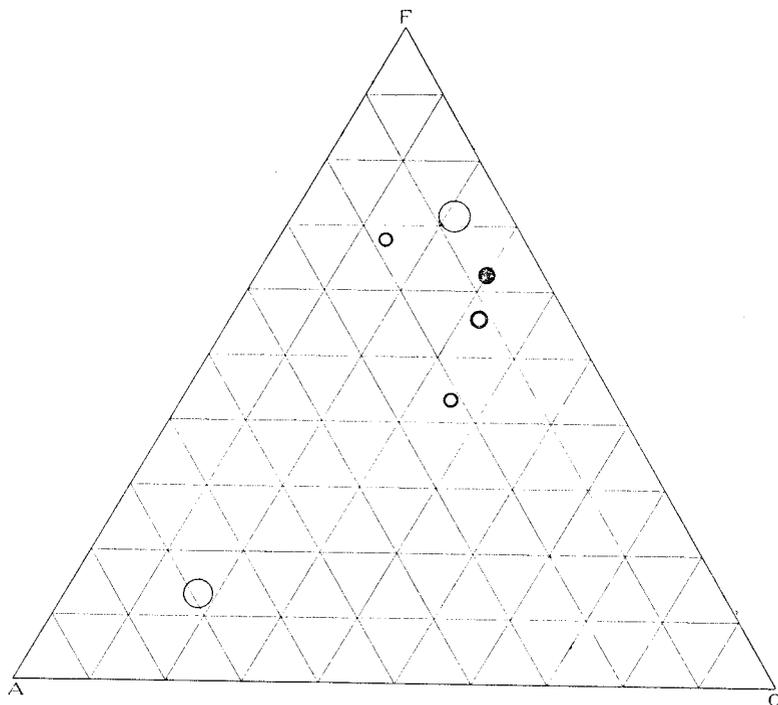


Fig. 13. Illustrates Osann's method of plotting analyses and their relations to albite or orthoclase (Lower left hand corner A), anorthite (lower right hand corner C), ferro-magnesian minerals (at the vertex F). The center of the circle is determined by the ratio of A:C:F in the analysis. Given in order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

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

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.

#### § 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 Keweenaw 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<sup>43</sup> calls attention is well worth noting.

<sup>43</sup>"Natural History of Igneous Rocks," p. 118.

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<sup>44</sup> that, on the whole, the Keweenaw 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:<sup>45</sup> 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.

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

<sup>44</sup>On September 2, 1910, after this report was written (in Science XXXII, p. 313) F. F. Grout published some excellent analyses of the Minnesota Keweenaw. 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 Keweenaw rocks, which curiously has the same percentage of copper shown by the Clark-Montreal sludge analyses. Grout also gives analyses of a number of minerals, of which the chloritic minerals are of especial interest.

<sup>45</sup>Compare especially with the group analyses 40 and 41 of Daly (Proc. Am. Ac. Arts and Sciences, Vol. XVI (1910) p. 224).

to the Keweenaw 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 Keweenaw rocks are almost unknown. The acmite syenite cutting the Virginia slates<sup>46</sup> and possibly the rocks referred to by Adams<sup>47</sup> are the nearest to exceptions. Occasionally an analysis may (like Bed 87 of the Eagle River section) figure out a little nepheline, but I have never recognized any, though secondary analcite occurs. Now it is suggestive that while the Keweenaw 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 Keweenaw 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 Keweenaw 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 Keweenaw 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.<sup>48</sup>

<sup>46</sup>Report for 1908, p. 394. Also Winchell, M. H. Proc. L. S., M. J.

<sup>47</sup>Journal of Geology, VIII, (1900) p. 322.

<sup>48</sup>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.

The eutectic line<sup>49</sup> 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 hypereutectic 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  $\text{RSiO}_3$  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<sup>50</sup> 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 broto crystals, 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  $\text{SiO}_2$  there should not be so much of a tendency to form  $\text{FeO Fe}_2\text{O}_3$  as  $\text{FeO SiO}_2$  and  $\text{Fe}_2\text{O}_3$ . 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

<sup>49</sup>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.

<sup>50</sup>Analyses of igneous rocks, U. S. Geol. Survey Professional Paper No. 14, 1903.

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 ( $2\text{MgO SiO}_2$ ) instead of enstatite ( $\text{MgO SiO}_3$ ) as the rhyocrystal formed. Now, it is characteristic of the Keweenaw 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 Keweenaw analyses above the eutectic trough as shown in Figure 12.

#### § 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<sup>51</sup> 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  $800^\circ\text{C}.$ , while the quartz and feldspar remain in solution to be deposited as pegmatite between  $800^\circ$  and  $550^\circ$  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

<sup>51</sup>Tufts College Studies, Vol. III, No. 1, p. 40.

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  $\text{SiO}_2:\text{Na}_2\text{O} = 12:1$  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.<sup>52</sup> 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 potassic 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

<sup>52</sup>Tables 12 to 15.

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 yet, 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.

#### § 8. SECONDARY CHEMICAL CHANGES.

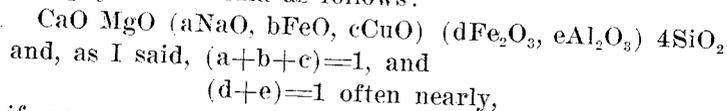
Another interesting question pertains to the metamorphosis or change of the rocks after consolidation. No sharp line can be drawn here between the final consolidation and a work of change which at once begins. Judging by all we know the lava will be a solid rock at something not far below 900°C., and the quartz will not crystallize above 800°C., and most of the quartz of the felsites and quartz diabases was probably formed between 800°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<sup>53</sup> 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.

§ 9. HYDRATION YIELDING NATIVE COPPER.

In my paper before the Lake Superior Mining Institute<sup>54</sup> 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:



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

<sup>53</sup>Chemical and Geological Essays, pp. 122, 138, 151.  
<sup>54</sup>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 wall rock at the Winona Mine (p. 583) seem to check very well with the formation of epidote assumed in this section.

HYDRATION YIELDING NATIVE COPPER.

Molecule	4 SiO <sub>2</sub>	d Al <sub>2</sub> O <sub>3</sub>	e Fe <sub>2</sub> O <sub>3</sub>	b FeO	c CuO	CaO	MgO	a (Na <sub>2</sub> O, K <sub>2</sub> O)	Add H <sub>2</sub> O
All Al <sub>2</sub> O <sub>3</sub> as Aurifer	d SiO	d Al <sub>2</sub> O <sub>3</sub>					2d MgO		2d
H <sub>4</sub> Mg <sub>2</sub> Al <sub>2</sub> SiO									
Balance, Mg as Serpentine	2-3(1-2d) SiO <sub>2</sub>						3-3(1-2d) MgO		2-3(1-2d)
H <sub>2</sub> Mg <sub>3</sub> Si <sub>2</sub> O <sub>9</sub>									
All iron as Epidote	6-6(2e+b)		3-6(2e+b) Fe <sub>2</sub> O <sub>3</sub>	1-2 1/4	1-2 bCu	4-6(2e+b) = 0			1-6(2e+b)
H <sub>2</sub> Ca <sub>4</sub> Fe <sub>6</sub> Si <sub>6</sub> O <sub>26</sub>			{ 3eO + 9.6H <sub>2</sub> O } = 1 - 3/4 6O }		if c = 1-2 b				
Na <sub>2</sub> O 4SiO <sub>2</sub>								a	
in solution	4a							= 0	
Water glass									

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<sub>2</sub>O<sub>3</sub> 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  
 a = 1 - 3c  
 b = 2c  
 d = .25 + c  
 e = .75 - c

Assuming, then, that c=0.109 we may obtain the following values:  
 c = .109  
 b = .338  
 a = .493  
 e = .581  
 d = .419

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 bodies, and *does not affect the conclusions.*  
 Quartz = 0 = 4 - 2-3(1-2d) - (2e+b) - 4a  
 = 1.83 - 4a + 1-3d = -2.083 + 1-2 - 1-3c

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  $\text{Fe}_2 \text{O}_3$  was largely  $\text{Al}_2 \text{O}_3$ . Transferring then .419 molecules from ferric 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 percentages (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
Si O <sub>2</sub> .....	4.000	.753	.753	4.000	.753	45.2	241.6
Al <sub>2</sub> O <sub>3</sub> .....	.419	.079	.155	.838	.158	16.1	85.9
Fe <sub>2</sub> O <sub>3</sub> .....	.581	.109	.120	.162	.030	4.9	25.9
Fe O.....	.338	.064	.061	.338	.064	4.6	24.3
Mg O.....	1.000	.188	.179	1.000	.188	7.5	40.4
Ca O.....	1.000	.188	.185	1.000	.188	10.6	56.1
Na <sub>2</sub> O.....	.493	.093	.042	.493	.093	5.8	30.6
K <sub>2</sub> O.....							
H <sub>2</sub> O+.....				Added		Added	
H <sub>2</sub> O-.....				1.196	.226	4.1	21.6
Ti O <sub>2</sub> .....							
P <sub>2</sub> O <sub>5</sub> .....							
CO <sub>2</sub> .....							
S.....							
SO <sub>3</sub> .....							
Cu O.....	.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/.753.

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 paragenesis of the minerals associated with copper<sup>55</sup> 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

<sup>55</sup>Vol. I, pt. II, Chapter III, p. 37.

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. 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 <sub>2</sub> .....	36.75 = .612 molecule.
Alumina and { or as FeO).....	24.57 = .294
Iron oxide { (Fe <sub>2</sub> O <sub>3</sub> , Al <sub>2</sub> O <sub>3</sub> ).....	27.34
Magnesia, MgO.....	23.24 = .581
Loss on ignition H <sub>2</sub> O; CO <sub>2</sub> .....	11.07 = .616
Difference Na <sub>2</sub> O + K <sub>2</sub> O?.....	1.6 = .026?
	100.00

This evidently corresponds closely to a formula 2H<sub>2</sub>O, 2MgO, FeO, 2SiO<sub>2</sub> closely allied to that of serpentine. Serpentine is often derived from peridotites. 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 ferric (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<sub>2</sub>.

#### 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  $3^{\circ}$ — $3^{\circ}$ , in another case  $7^{\circ}$ — $7^{\circ}$  and generally small (in one case in that zone 10—15) ? ( $18^{\circ}$ — $18^{\circ}$ ).

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 ( $\text{Na}_2\text{Si}_4\text{O}_9$ ) and serpentine introduced ( $\text{H}_4\text{Mg}_3\text{Si}_2\text{O}_9$ ) 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 conglomer-

ate 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 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  $2\text{H}_2\text{O}:1\text{Al}_2\text{O}_3$ ,—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.<sup>56</sup> 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.<sup>57</sup> 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.<sup>58</sup> 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.<sup>59</sup> 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

<sup>56</sup>Point Houghton, see Vol. VI, also Bull. 8, Minn. Sur. XXXIII, Ser. No. 165, Geol. Sur. No. 555, J. A. Dodge, analyst.  
<sup>57</sup>Analysis 2 of Table XIX. Core at 500 feet of White Pine Exploration, d. 34.  
<sup>58</sup>The palladium also suggests this.  
<sup>59</sup>Geology of Wisconsin, Vol. III, p. 350.

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<sup>60</sup> 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.

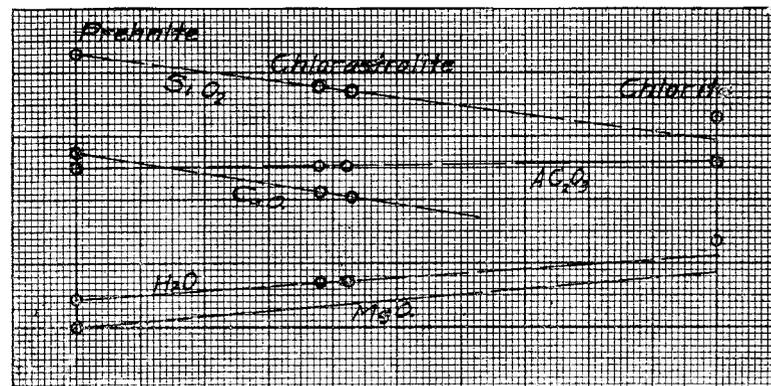


Fig. 14. Illustrates relation of prehnite, chlorastrolite and chlorite. In this diagram the percentages of silica are the abscissa, while the other elements are shown by ordinates as indicated on the diagram.

<sup>60</sup> 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 hard gravel material.

<sup>61</sup>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	5.63	7.89
Silica	55.08	41.31
Iron oxide, Fe <sub>2</sub> O <sub>3</sub>	9.04	12.90
Alumina, (+ tr. Ti O <sub>2</sub> )	15.41	22.46
Lime (Ca O)	7.02	11.08
Magnesium Oxide, (Mg O)	2.49	4.07
Chlorine	.18	.11
Sulphur tri-oxide (SO <sub>3</sub> )	.64	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.

§ 13. CONCENTRATION OF CHLORITIC MATERIAL.

One of the commonest changes throughout the Keweenaw 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.<sup>61</sup> 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?	increase	decrease
$FeO$ .....	.....	.....	.....	.....	.....	decrease
$MgO$ .....	increase	.....	.....	.....	.....	decrease
$CaO$ .....	.....	.....	.....	.....	.....	decrease
$Na_2O$ .....	.....	.....	.....	.....	.....	decrease
$K_2O$ .....	decrease	.....	.....	.....	.....	decrease
$H_2O$ .....	.....	decrease	decrease	.....	decrease	.....
$H_2O+$ .....	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

<sup>61</sup>See also Grant's paper in Science 1910, Vol. XXXII, p. 312, and U. S. G. S. Monog. 52, p. 582.

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  $1Al_2O_3$ . 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 ( $Na_2O \cdot 4SiO_2$ ) 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 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<sup>62</sup> 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

<sup>62</sup>Ex. Doc. No. 5, 31st Congress, 1849.

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 amygdaloid 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 Keweenaw traps is, therefore, about 2,880 ounces or 180 pounds per cubic foot.



nal 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
Si O <sub>2</sub>	46.98	.783	47.67	.794	47.25	.787	47.10	.785
Al <sub>2</sub> O <sub>3</sub>	17.85	.174	17.55	.171	18.00	.176	17.47	.170
Fe <sub>2</sub> O <sub>3</sub>	3.13	.029	2.51	.015	2.21	.014	2.66	.016
Fe O	10.36	.143	12.69	.176	12.42	.172	12.93	.179
Mg O	7.16	.178	5.65	.141	6.35	.159	6.88	.172
Ca O	8.47	.151	10.75	.192	11.45	.204	10.27	.183
Na <sub>2</sub> O	2.04	.032	2.21	.035	1.96	.030	1.91	.031
K <sub>2</sub> O	.60	.006	.65	.006	.66	.006	.59	.005
H <sub>2</sub> O	1.45	.081	.05	.002				
H <sub>2</sub> O+	3.02	.167	2.02	.112				
Ti O <sub>2</sub>								
P <sub>2</sub> O <sub>5</sub>	.143	.001	.169	.001	.158	.001	.161	.001
CO <sub>2</sub>								
S	.097	.002	.183	.004	.086	.002	.111	.003
SO <sub>3</sub>								
Mn O	.26	.003	.19	.002	.18	.002	.15	.001
Cl	.07	.001	.05	.001	.02	.001	.09	.002
Alkali m.	101.80	1.742	102.422	1.652	100.744	1.554	109.522	1.547
Silica m.		.048		.053		.047		.0472
Pore space to solid space		.0473		.0012		.0032		.0018
Sp. Gr.		2.83		3.02		3.01		3.02

<sup>1</sup>Taken in gasoline.

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 Keweenaw 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 Keweenaw 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).

	1	1a	2	2a	3	3a	4	5	5a
Si O <sub>2</sub>	47.70	.795	47.90	.798	49.78	.830	53.38	35.81	.596
Al <sub>2</sub> O <sub>3</sub>	19.04	.186	19.92	.195	29.37	.288	29.70	14.32	.140
Fe <sub>2</sub> O <sub>3</sub>	.87	.005	4.92	.030	.34	.002	.21	7.38	.046
Fe O	8.84	.123	9.78	.137	.60	.008		15.25	.211
Mg O	8.65	.216	4.55	.113	1.01	.025	tr.	10.49	.262
Ca O	8.96	.159	8.56	.152	11.86	.211	11.90	17.23	.307
Na <sub>2</sub> O	2.53	.041	2.75	.044	4.39	.071	4.30	2.06	.033
K <sub>2</sub> O	.53	.005	.56	.005	.46	.005	.56	.37	.003
H <sub>2</sub> O									.291
H <sub>2</sub> O+	1.38	.078	.76	.043	1.76	.097	.37	5.23	
Ti O <sub>2</sub>	1.80	.022	.57	.006				2.30	.028
P <sub>2</sub> O <sub>5</sub>	n. d.								
CO <sub>2</sub>									
S									
SO <sub>3</sub>									
Mn O	tr.		tr.		.08	.001		.18	.002
Ba, SrO	.00								
Al. m.	100.30	1.629	100.27	1.523	99.80	1.538	100.42	100.62	1.919
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
Si O <sub>2</sub> .....	52.48	.875	49.15	.819	45.65	.760	46.29
Al <sub>2</sub> O <sub>3</sub> .....	15.47	.152	21.90	.215	15.20	.149	18.20
Fe <sub>2</sub> O <sub>3</sub> .....	5.14	.032	6.60	.041	6.71	.042	4.98
Mg O.....	9.25	.128	4.54	.063	13.81	.192	5.52
Ca O.....	2.55	.063	3.03	.076	2.95	.074	8.24
Na <sub>2</sub> O.....	7.27	.130	8.22	.146	6.33	.113	8.86
K <sub>2</sub> O.....	3.26	.052	3.83	.062	3.09	.050	3.30
H <sub>2</sub> O.....	1.75	.018	1.61	.017	1.05	.011	.76
H <sub>2</sub> O+.....	1.24	.068	1.92	.107	2.29	.127	3.42
Ti O <sub>2</sub> .....	1.26	.014	.18	.002	1.66	.020	
P <sub>2</sub> O <sub>5</sub> .....	.29	.001	.33	.002	.25	.001	
CO <sub>2</sub> .....							
S.....			Cu, p. n. d.				
SO <sub>3</sub> .....			n. d.				
Mn <sup>+</sup> O.....	.51	.007	n. d.		.71	.010	
Alkali m.....	100.47	1.540	101.31	1.550	100.70	1.549	
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<sub>2</sub> and P<sub>2</sub>O<sub>5</sub> 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 Teal'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 rocks 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 porphyry, 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
Si O <sub>2</sub> .....	76.67	1.277	76.48	48.47	.807	51.75	.862	73.37	1.222
Al <sub>2</sub> O <sub>3</sub> .....	14.23	.128	12.06	30.16	.147	28.31		16.09	
Fe <sub>2</sub> O <sub>3</sub> .....		.013	0.95		.095?				
Fe O.....									
Mg O.....	0.28	.007	0.39	6.89	.172	6.13	.153	1.05	.026
Ca O.....	1.44	.026	0.64	11.87	.211	10.65	.190	2.66	.048
Na <sub>2</sub> O.....	4.18	.068	4.89	1.96	.031	2.20	.035	3.93	.063
K <sub>2</sub> O.....	3.20	.034	3.78	0.65	.006	0.96	.010	2.90	.031
H <sub>2</sub> O.....									
H <sub>2</sub> O+.....			70.77						
Ti O <sub>2</sub> .....									
P <sub>2</sub> O <sub>5</sub> .....									
CO <sub>2</sub> .....									
S.....									
SO <sub>3</sub> .....									
Alkali m.....		.080	.097		.045				
Silica m.....									
	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. Reygaldr Foss.
- 4a. Molecular proportions.
5. Klettberge.
- 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
Si O <sub>2</sub>		53.30	49.80	45.05	48.34	33.57
Al <sub>2</sub> O <sub>3</sub>		29.03	2.86	.16	2.90	
Fe <sub>2</sub> O <sub>3</sub>	50.29	.55	2.48	5.50	4.68	
Fe O	30.70	.23	10.82	14.90	14.15	48.74
Mg O		.13	15.33	15.15	11.34	17.69
Ca O		11.40	16.50	10.72	15.10	
Na <sub>2</sub> O		-4.87	.51	1.27		
K <sub>2</sub> O		.40	.12	.78		
H <sub>2</sub> O		.23	.33	.13	1.98	
H <sub>2</sub> O+						
Ti O	8.77	trace	1.29	4.39		
P <sub>2</sub> O <sub>5</sub>		trace	trace			
CO <sub>2</sub>						
Sr O		trace	none			
Li <sub>2</sub> O		none	trace?			
Mn O		none	trace	1.58		
Ba O		trace	none			
Sp. Gr.	89.46	100.14	100.41	99.63 3.316	98.49	

1. Magnetite.
2. Labradorite Ab<sub>10</sub> An<sub>60</sub>.
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.

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. Mendellhall's mine, p. 513.
17. F. & W. II, p. 88. Hydrus epidote?

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

TABLE VI.—Miscellaneous old analyses from reports of Jackson<sup>1</sup> and Foster and Whitney<sup>2</sup> showing composition of various secondary minerals.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Si O <sub>2</sub>	8.91	57.95		52.7	51.000	53.40		49.09	49.06	46.12	37.41	36.99	94.24 <sup>2</sup>	81.10	55.04	BaSO <sub>4</sub> 64.1	42.6
Al <sub>2</sub> O <sub>3</sub>		19.00				22.40		.23	1.28	25.91	24.25	25.49	.47	2.61	22.34	SiO <sub>2</sub> 64	31.2
Fe O	1.98										6.26	6.48	.92 <sup>2</sup>	3.91			
MgO		13.06		23.35	24.944	3.00		.14									
CaO	+ CO <sub>2</sub> 44.65	1.32		4.95		8.52		46.38	44.87	27.03	21.08	19.90	+ CO <sub>2</sub> .07	.25			
Na <sub>2</sub> O	+ CO <sub>2</sub> 44.49	1.05								.85	4.88	3.70	+ SO <sub>4</sub> .06	.22			
K <sub>2</sub> O					5.187								Org 2.92				
H <sub>2</sub> O		7.81		16.00	16.00	10.31		2.96	2.96		5.77	7.22		8.93	11.93		20.6
H <sub>2</sub> O+			4.4											2.79	6.97		5.2
Ti O <sub>2</sub>																	
P <sub>2</sub> O <sub>5</sub>																	
CO <sub>2</sub>								Mn O .48	.90								
S																	
SO <sub>3</sub>				1.85	1.94												
Cu F																	
Sp. Gr.	100.03	99.19		98.85	99.071	97.63		100.00	100.00	99.91	100.25	100.18					99.6
				2.305		2.250 to 2.258						3.18					

<sup>1</sup>House Ex. Doc., No. 5, 31st Congress, 1st Session.  
<sup>2</sup>Report on the Geology of the Lake Superior Land District, Pt. III, 1851. Ex. Doc. No. 5. Special session of Senate, March 1851.

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
Si O <sub>2</sub> .....	75.67	1.261	80.05	1.332	69.76	1.162
Al <sub>2</sub> O <sub>3</sub> .....	12.43	.121	9.73	.095	13.14	.128
Fe <sub>2</sub> O <sub>3</sub> .....	2.27	.014	1.72	.010	1.44	.009
Mg O.....	0.15	.002	0.18	.002	0.66	.009
Ca O.....	0.00	.000	0.00	.000	0.18	.004
Na <sub>2</sub> O.....	tr.		0.83	.014	0.36	.006
K <sub>2</sub> O.....	2.01	.032	2.19	.035	2.52	.040
H <sub>2</sub> O.....	6.73	.071	4.43	.047	11.90	.126
H <sub>2</sub> O+.....	0.41	.022	1.03	.057	0.42	.024
Ti O <sub>2</sub> .....						
P <sub>2</sub> O <sub>5</sub> .....						
CO <sub>2</sub> .....						
S.....						
SO <sub>3</sub> .....						
Mn O.....						
Alkali m. }.....	tr.		tr.			
Silica m. }.....		.082		.066		.143
	99.67	1.521	100.16	1.589	100.38	1.499

1<sup>1</sup> Hubbard, p. 28.

1a. Molecular proportions.

2. 17193 A<sup>2</sup> end of Mt. Houghton. Hubbard, p. 42.

2a. Molecular proportions.

3. 16951 Mt. Houghton, south (lower) side.

3a. Molecular proportions.

<sup>1</sup>1 does not fuse at 900°, cakes and bleaches, has few small phenocrysts of feldspar.  
<sup>2</sup>17193A shows infiltrated quartz.

TABLE VIII.

Transition rocks, porphyrite flows below Mount Houghton quartz porphyry. From L. L. Hubbard, F. P. Burrell, 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
Si O <sub>2</sub> .....	52.83	.880	51.45	.957	59.52	.991
Al <sub>2</sub> O <sub>3</sub> .....	16.30	.160	15.75	.154	15.58	.153
Fe <sub>2</sub> O <sub>3</sub> .....	9.60	.060	11.12	.069	7.24	.045
Fe O.....	2.48	.035	1.74	.024	1.86	.027
Mg O.....	3.98	.099	1.94	.048	2.11	.052
Ca O.....	2.98	.053	0.12	.002	1.81	.032
Na <sub>2</sub> O.....	6.54	.105	7.84	.126	6.82	.109
K <sub>2</sub> O.....	2.49	.025	3.51	.037	3.48	.036
H <sub>2</sub> O.....						
H <sub>2</sub> O+.....	2.76	.153	1.23	.067	2.23	.123
Ti O <sub>2</sub> .....						
P <sub>2</sub> O <sub>5</sub> .....						
CO <sub>2</sub> .....						
S.....						
SO <sub>3</sub> .....						
Alkali m. }.....		.148		.170		.147
Silica }.....						.147
Sum.....	99.96	1.567	100.70	1.484		1.572

1. 17033 Hubbard, p. 25, diabase porphyrite, Bed E.<sup>1</sup>

1a. Molecular proportions.

2. 17007 Hubbard, p. 26.<sup>2</sup>

2a. Molecular proportions.

3. 17039<sup>3</sup> p. 26.

3a. Molecular proportions.

<sup>1</sup>Fusible about 900° C with microlitic ground mass and phenocrysts. Bed E of the Mt. Houghton felsite series.

<sup>2</sup>Feldspar near albite. Cf. gabbro aplites, Bed G. Separated from E by amygdaloid conglomerate, 915N., 1060 W. Sec. 20, T. 58 N., R. 28 W.

<sup>3</sup>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<sub>2</sub> 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. Cf. Bowen's Gowganda, and the Cobalt (Canada) aplites,<sup>1</sup> 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. Kirschbraum 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.	
Si O <sub>2</sub>	64.53	1.075	62.28	1.038	Quartz	12.90
Al <sub>2</sub> O <sub>3</sub>	4.13	.041	17.54	.171	Orthoclase	17.78
Fe <sub>2</sub> O <sub>3</sub>	2.73	.017	1.55	.010	Albite	36.18
Mg O	12.82	.178	5.64	.078	Anorthite	17.23
Ca O	2.13	.053	1.51	.038	Corundum	.92
Na <sub>2</sub> O	4.35	.078	3.44	.062	Hypersthene	11.07
K <sub>2</sub> O	0.24	.004	4.26	.069	Ilmenite	1.98
H <sub>2</sub> O	3.86	.041	2.97	.032	Magnetite	2.32
H <sub>2</sub> O+	0.20	.011				
Ti O <sub>2</sub>	2.60	.144				
P <sub>2</sub> O <sub>5</sub>	.63	.008	.98	.013		
CO <sub>2</sub>	0.41	.003				
S	tr.					
SO <sub>3</sub>	0.62	.008				
Mn O	0.79	.011				
Alkali m.	100.04	1.672	100.17	1.511		100.38
Silica		.041	.098			
Sp. Gr.		2.668				

<sup>1</sup>Journal of the Can. Min. Inst. XII., 1909, p. 517.

- 5. Gabbro aplitite. Cook loc. cit.
- 5a. Molecular proportions.
- 6. Gabbro aplitite. 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
Si O <sub>2</sub>	45.30	.753	46.01	.766
Al <sub>2</sub> O <sub>3</sub>	11.81	.116	16.95	.167
Fe <sub>2</sub> O <sub>3</sub>	9.94	.062	5.14	.032
Fe O	9.31	.129	9.83	.137
Mg O	8.09	.202	6.20	.155
Ca O	8.05	.144	6.71	.120
Na <sub>2</sub> O	0.93	.014	2.22	.035
K <sub>2</sub> O	4.07	.043	1.71	.018
H <sub>2</sub> O	0.30	.017		
H <sub>2</sub> O+	2.70	.150		
Ti O <sub>2</sub>	1.15	.014	2.48	.031
P <sub>2</sub> O <sub>5</sub>	0.80	.006		
CO <sub>2</sub>	1.49	.034		
S				
SO <sub>3</sub>	0.72	.009		
Mn O	0.84	.012		
Alkali m.	105.50	1.707	97.25	1.461
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
Si O <sub>2</sub>	44.91	.748	47.01	.783	45.69	45.85	45.9	.765
Al <sub>2</sub> O <sub>3</sub>	18.01	.176	17.80	.174	14.44	10.97?	15.15	.148
Fe <sub>2</sub> O <sub>3</sub>	4.50	.028	5.32	.033	6.21	4.97	5.00	.031
Fe O	7.64	.106	6.59	.092	9.39	13.79	8.00	.111
Mg O	7.67	.192	8.75	.219	2.19	1.61	8.00	.200
Ca O	7.49	.134	5.31	.095	7.44	5.71	7.5	.134
Na <sub>2</sub> O	1.75	.028	2.00	.032	0.96	0.91	2.00	.032
K <sub>2</sub> O	1.33	.014	1.58	.017	6.96!	9.29?	1.5	.016
H <sub>2</sub> O	4.16		3.45		0.55	0.35	.45	.026
H <sub>2</sub> O+	by diff.		by diff.		2.35	2.55	2.45	.136
Ti O <sub>2</sub>	2.54	.030	2.19	.026	1.90	1.69	2.00	.024
P <sub>2</sub> O <sub>5</sub>					0.32	0.38	.35	.002
CO <sub>2</sub>					tr.			
S								
SO <sub>3</sub>					1.30	1.78	1.5	.019
Mn O					0.33	0.14	.2	.003
		1.456						
Alkali m.	95.84		96.55	1.471	100.03	99.99	100.00	
Silica m.		.055		.063				.063

1. Normal ophite, Sp. 2, F. E. W. 21. This seems low in CaO and SiO<sub>2</sub> 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
Si O <sub>2</sub> .....	50.07	.834	46.45	0.774	49.27	.834	50.03
Al <sub>2</sub> O <sub>3</sub> .....	12.63	.123	16.60	0.163	16.75	.150	15.38
Fe <sub>2</sub> O <sub>3</sub> .....	3.84	.024	2.72	0.017	7.78	.073	11.78
Fe O.....	10.30	.143	7.25	0.100	4.86	.054	3.90
Mg O.....	5.23	.131	9.21	0.230	7.44	.090	3.60
Ca O.....	6.55	.117	6.32	0.112	5.47	.094	5.39
Na <sub>2</sub> O.....	3.53	.056	4.05	0.065	5.42	.080	5.01
K <sub>2</sub> O.....	1.90	.020	1.02	0.010	0.48	.012	1.14
H <sub>2</sub> O.....	0.86	.048	loss	on ign			
H <sub>2</sub> O+.....	1.96	.109	5.01	0.278	3.72?	.150	2.73
Ti O <sub>2</sub> .....	2.50	.030					
P <sub>2</sub> O <sub>5</sub> .....	0.22	.001					.33
CO <sub>2</sub> .....	0.00	.000	0.40	0.009	0.92	.020	0.98
S.....							
SO <sub>3</sub> .....							
Mn O.....	0.42				Trace		
Ba O.....	0.02						
Alkali m.....	100.03	1.636	99.03	1.758	101.19	1.557	99.94
Silica m.....	.091			.098		.111	

1. Bed 65<sup>1</sup> Eagle River.
  - 1a. Molecular proportions.
2. 15515 Isle Royale, p. 146.<sup>2</sup>
  - 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.

<sup>1</sup>Journal of Geol. XVI, p. 772.

<sup>2</sup>Vol. VI, Part I, pp. 215, 143, 146.

TABLE XIII.

Melaphyre analyses of uncertain affinities. No. 1 (see Vol. VI, p. 215) is 16 feet from the top of a typical "Ashbed" melaphyre porphyrite. No. 2 is from the middle of a bed (Eagle River S7), 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
Si O <sub>2</sub> .....	46.99	.783	49.20	.820	47.97	.799
Al <sub>2</sub> O <sub>3</sub> .....	18.47	.181	16.00	.157	15.56	.152
Fe <sub>2</sub> O <sub>3</sub> .....	4.44	.027	3.03	.019		
Fe O.....	7.24	.100	7.10	.099	12.41	.172
Mg O.....	6.03	.151	6.98	.175	8.28	.207
Ca O.....	9.53	.169	3.44	.061	7.07	.126
Na <sub>2</sub> O.....	3.37	.054	5.05	.081	6.24	.100
K <sub>2</sub> O.....	0.33	.003	1.31	.014		
H <sub>2</sub> O.....	3.90	.216	4.51	.250	2.46	.137
H <sub>2</sub> O+.....	loss					
Ti O <sub>2</sub> .....			2.26	.027		
P <sub>2</sub> O <sub>5</sub> .....						
CO <sub>2</sub> .....						
S.....						
SO <sub>3</sub> .....						
Mn O.....	trace		1.17	.016		
Alkali m.....	100.30	1.684		1.719	99.99	1.693
Silica m.....		.073		0.114		0.125
Sp. Gr.....	2.901					

1. 15533<sup>1</sup> Isle Royale, p. 215.
  - 1a. Molecular proportions.
2. Eagle River Bed No. S7.
  - 2a. Molecular proportions.
3. Rock Harbor trap, F. & W., Pt. II, p. 88.
  - 3a. Molecular proportions.

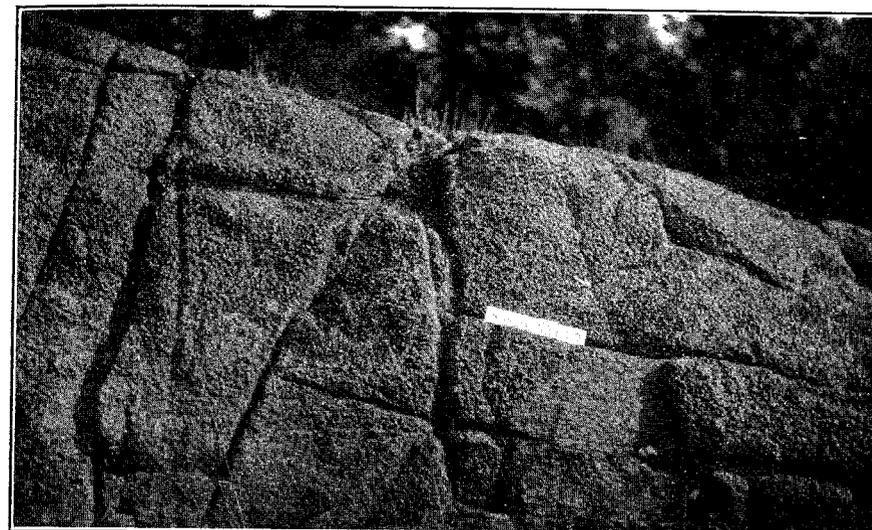
<sup>1</sup>At the page cited will be found another check analysis which is from the same bed, 3 feet farther from the top. This is 16 feet from the top. It is the same bed as 15537 but has more lime.

TABLE XIV.

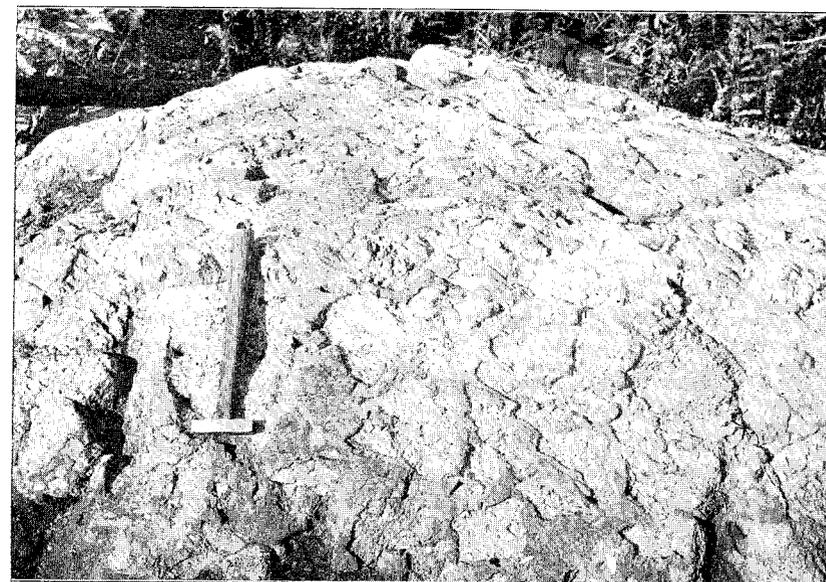
Analyses of the great flow known as the "Greenstone,"—typically an ophite, at any rate at the base, (see Pls. II and III) though large plagioclase rhyocrystals occasionally occur. None of the analyses are satisfactory. The Foster and Whitney (1) and Jackson analyses (3) are old and incomplete, and the 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
Si O <sub>2</sub> ...	>50.20	.836	26.08	47.69	.795	51.28	.855	47.2	45.2
Al <sub>2</sub> O <sub>3</sub> ...	15.43	.151	7.22	16.02	.157	17.12	.168	15.8	16.1
Fe <sub>2</sub> O <sub>3</sub> ...				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 <sub>2</sub> O...	4.75	.076	1.22	2.44	.039				5.8
K <sub>2</sub> O...					.000				
H <sub>2</sub> O...	1.74	.097	1.55	0.44	.025				4.1
H <sub>2</sub> O+				2.04	.114				
TiO <sub>2</sub> ...				1.38	.016				
P <sub>2</sub> O <sub>5</sub> ...				0.06	.001				
CO <sub>2</sub> ...					.000				
S...					.000				
SO <sub>3</sub> ...					.000				
MnO...				0.26	.003	0.99	.014	0.9	CuO .2.6
	100.00	1.664		100.29	1.680	100.17	1.610	99.9	101.3
Alkali m.		.094			.049				
Silica m									

1. F. & W. Pt. 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, Sp. 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<sub>2</sub>O<sub>3</sub> to make the amount of iron



(A.) WEATHERED SURFACE OF OPHITE TAKEN AT ABOUT THE SAME TIME AS PLATE II BY W. J. PENHALLEGON.



(B.) WEATHERED SURFACE OF AMYGDALOID CONGLOMERATE AFTER FIGURE 2, PART 2 OF VOLUME VI.

generally found in the Greenstone,—say 8.3%  $\text{FeOFe}_2\text{O}_3$ —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.

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
Si O <sub>2</sub> . . . .	46.13	.769	46.25	46.32	.771	46.48	45.21	.753	49.3
Al <sub>2</sub> O <sub>3</sub> . . . .	19.79	.194	18.39	15.95	.156	17.71	15.85	.155	10.1
Fe <sub>2</sub> O <sub>3</sub> . . . .	7.24	.045	7.70	2.86	.018	21.17	9.55	.059	3.9
Fe O . . . . .	3.79	.053	3.52	8.92	.124		4.37	.061	4.0
Mg O . . . . .	7.27	.182	4.65	4.08	.102	tr.	7.25	.181	11.8
Ca O . . . . .	11.43	.203	12.19	10.28	.184	9.89	10.36	.185	12.2
Na <sub>2</sub> O . . . .	2.55	.041	3.76	3.56	.057	by diff.	2.47	.039	2.6
K <sub>2</sub> O . . . . .	0.52	.005	1.04	1.23	.013	1.97	.47	.003	.2
H <sub>2</sub> O . . . . .	1.83	.101	3.41	3.25	.180	2.78	.31	.026	
H <sub>2</sub> O+ . . . .							.41	.023	
Ti O <sub>2</sub> . . . . .				2.78	.034		2.14	.025	1.6
P <sub>2</sub> O <sub>5</sub> . . . . .							.165	.001	
CO <sub>2</sub> . . . . .	0.29	.006	1.00				.48	.011	
S . . . . .							.07	.002	
SO <sub>3</sub> . . . . .									
Mn O . . . . .	Trace			0.89	.013		.89	.013	.9
Cl . . . . .							.04	.001	
Moisture . . . .							.47	.026	
Alkali m . . . .	100.84	1.599	101.91	100.12	1.652	100.00		1.564	
Silica m . . . .		.0599			.091			.056	

1. Ophitic streak 9 feet from base of same (77-foot) bed as 15515 and 15519, Eagle River 39-43, 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 Sauk 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
Si O <sub>2</sub> .....			31.78	33.14	30.59	57.95	36.99	19.22
Al <sub>2</sub> O <sub>3</sub> .....	30.95	.303	15.47	13.22	26.07	19.00	25.49	13.90
Fe <sub>2</sub> O <sub>3</sub> .....			24.20				6.48	
Fe O.....	32.47	.453	28.87	12.19	22.01	13.06		6.54
Mg O.....	15.98	.399	4.37	3.49	12.36	1.32		
Ca O.....	9.36	.167	9.64	1.50	1.92	.05	19.90	6.40
Na <sub>2</sub> O.....	11.26	.181					3.70	
K <sub>2</sub> O.....			9.87	12.34	7.23	7.81	7.22	6.40
H <sub>2</sub> O.....								
H <sub>2</sub> O f.....								
Ti O <sub>2</sub> .....								
P <sub>2</sub> O <sub>5</sub> .....								
CO <sub>2</sub> .....								
S.....								
SO <sub>3</sub> .....								
	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 walls. 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<sub>2</sub>, 24.78 Al<sub>2</sub>O<sub>3</sub>, 27.16 CaO, 4.37 H<sub>2</sub>O 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
Si O <sub>2</sub> .....	75.67	59.92	55.03	31.42	36.75	46.01	50.20	41.31	81.10	5.00
Al <sub>2</sub> O <sub>3</sub> .....	12.43	15.58	15.41 <sup>2</sup>	16.82	27.34	19.43	15.48	22.46	2.61	.43
Fe <sub>2</sub> O <sub>3</sub> .....	2.27	7.24	9.04	15.58		14.97 <sup>3</sup>	13.79	12.90	3.91	.02
Fe O.....	0.15	1.86		12.08						
Mg O.....	0.00	2.11	2.49	3.36	23.24	6.20	8.62	4.07	Mg CO <sub>3</sub> .25	.07
Ca O.....	tr.	1.81	7.02	2.84		6.71	5.47	11.08	Ca CO <sub>3</sub> 46.00	.32
Na <sub>2</sub> O.....	2.01	6.82	by diff. 4.01	1.98	1.6?	3.93	4.75	by diff. 0.04?		
K <sub>2</sub> O.....	6.73	3.48		1.04					Na <sub>2</sub> SO <sub>4</sub> K .22	.06
H <sub>2</sub> O.....	0.41	2.23	5.03	14.52	11.07		1.74	7.89	2.79	.73
H <sub>2</sub> O f.....			loss					loss	Organic	2.92
Ti O <sub>2</sub> .....									8.93	2.92
P <sub>2</sub> O <sub>5</sub> .....										
CO <sub>2</sub> .....										
S.....			Cl .18						.11	
SO <sub>3</sub> .....			.04					tr.		
Copper.....			1.70						.14	
			100.00	100.00	100.00	97.25	100.00	100.00		
				2.78						

<sup>1</sup>Loss on ignition.  
<sup>2</sup>With Ti O<sub>2</sub>.  
<sup>3</sup>Plus Fe O.  
<sup>4</sup>Na<sub>2</sub> O + K<sub>2</sub> O.

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.
5. Calumet conglomerate altered boulder, Heath. See § 10.
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 alkalis and rise in alumina are clear.

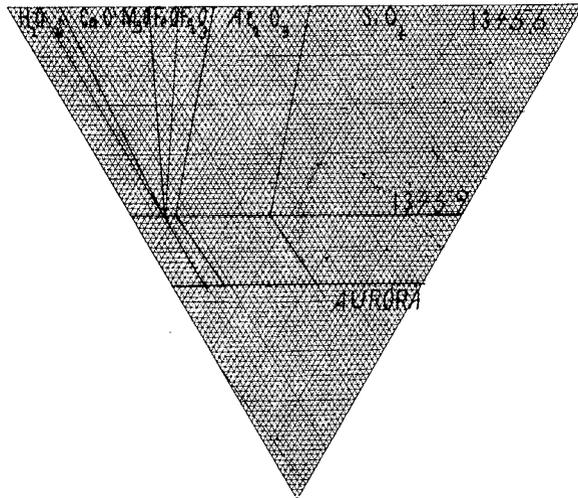


Fig. 15. Diagram illustrates abstraction of material attendant upon the alteration of diabase to kaolin.

TABLE XVIII.

Analyses illustrating kaolinitic alteration.

	1	1a	2	2a	3	4	5
SiO <sub>2</sub> .....	47.99	.83 .800	58.22	.970	47.90	46.85	41.60
Al <sub>2</sub> O <sub>3</sub> .....	16.57	.58 .162	28.66	.281	15.60	22.62	37.20
Fe <sub>2</sub> O <sub>3</sub> .....	6.01	2.35 .038	2.56	.016	3.69	5.12	3.21
P <sub>2</sub> O <sub>5</sub> .....	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 <sub>2</sub> O.....	2.00	.032			2.05	.80	.07
K <sub>2</sub> O.....	1.39	.015			0.23	2.66	
H <sub>2</sub> O.....		.25			.15	3.12	.29
H <sub>2</sub> O+.....	2.64	.148	10.50	.583	2.34	8.25	13.54
TiO <sub>2</sub> .....	2.71	.034			0.82	1.12	3.79
P <sub>2</sub> O <sub>5</sub> .....					.13	.16	.14
CO <sub>2</sub> .....					.38	1.89	.38
S.....					Cr <sub>2</sub> O <sub>3</sub> tr		
SO <sub>3</sub> .....					NiO.10	.08	
MnO.....	tr.				BaO.05	.10	
					.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<sub>2</sub>O, 3.48 Na<sub>2</sub>O, 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.