attending iron oxidation and concentration in the lava tops are also outlined above (p. 35), but some further details may pertinently be given before discussion of the cause of the behavior of oxygen and iron.

The texture of the upper, vesicular part of a flow is always finer than that of the trap in the same flow. The finest-grained, densest portions are at the very top of the smooth flows and around the margins of fragments of the brecciated tops. In these densest parts vesicles are plentiful but exceedingly small; deeper in the smooth flows or toward the center in the fragments the vesicles increase, in size, but the texture of the rock itself, though coarsening somewhat, remains comparatively fine so long as vesicles are plentiful.

All this fine-grained material is seen in thin section to comprise constituents of two kinds—minute crystals or microlites and a compact matrix which, despite especial efforts to obtain sections of unusual thinness, remains nontransparent. Among the transparent crystals feldspar predominates; it is present in delicate microlites of fairly perfect lath-shaped outline except for attenuated elongation of the sides of the crystal beyond the middle to give the characteristic pitchfork terminations. (See pl. 61.) This shape of the feldspars implies an increasing viscosity of the stir-rounding medium,[37] which was to be expected in these quickly chilling lava tops. Commonly the feldspar is strikingly clear and fresh, with plagioclase twinning easily seem (See pl. 61.) It ranges from oligociase-andesine to andesine; the feldspar of the trap portion is labradorite, in part highly calcic. Here and there are pseudomorphs whose outlines distinctly or vaguely suggest olivine but whose transparent part is now serpentine. Hematite is the only other recognizable mineral present (except for the vesicle fillings, which are of later introduction and are considered farther on). In these lavas, as in the lavas of Idaho, the hematite is partly in small ragged lumps or irregular spongy patches derived from, magnetite or olivine, but it mainly occurs as minute short crystalline plates distributed through the opaque matrix. For the most part this distribution of the hematite plates is even and systematic, suggestive of the intersertal pattern, but around the feldspar crystals and the vesicles the hematite particles appeal crowded and piled up, as if either pushed aside by or attracted to the expanding gas bubble or the growing feldspar microlite, neither of which contains hematite.

[37]Day, A. L., Allen, E. T., and Iddings, J. P., the Isomorphism and thermal properties of the feldspars: Carnegie Inst. Washington Pub. 31, p. 91, 1905.

The groundmass or matrix of these various crystals is opaque, probably because the hematite plates are so abundant as everywhere to overlap, even in a thin section. Presumably it is an undifferentiated material that contains the equivalent of the pyroxene present in the traps (but not crystallized, in these dense tops), as well as of additional feldspar, olivine, and magnetite. It is this groundmass which gives the red color to the lava tops, and the red color is plainly due to the hematite; the accordance between abundance and fineness of grain of the hematite, as seen under the microscope, and the intensity of the red color is notably close.

This dense rock of the upper part of the flows may thus be described as a devitrified glassy base containing microlites of feldspar and other minerals; such a description is allowable if devitrification is considered possible, as Geikie, Harker, and others believe, not only long after a rock is formed but also before a rock has lost its original heat and perhaps even before all of it has solidified.

CAUSE OF IRON OXIDATION AND CONCENTRATION

Several possible causes of the increase of ferric iron and of total iron toward the tops of the flows merit consideration—(*a*) present-day weathering; (*b*) action of solutions Independent in origin from the lavas; (*c*) normal weathering of the flow while exposed at the surface prior to covering by the next flow; (*d*) alteration by water or gases given off from later flows; (*e*) rapid atmospheric oxidation while the top of the flow was hot; (*f*) pneumatolytic alteration by gases given off by the lava of the flow itself before, during, and after solidification; (*g*) direct magmatic segregation.

MODERN WEATHERING

Modern weathering may be eliminated by the following considerations and dismissed without further argument: The oxidation is clearly earlier than the copper, which as shown in the discussion of ore deposition (p. 53) is not of recent formation; and the oxidation of a given flow is the same at a vertical depth of 5,000 feet, where the rocks are tight and dry, as it is in the zone of actively circulating ground waters.

INDEPENDENT SOLUTIONS

Under the action of independent solutions may be considered two unrelated influences—the action of circulating oxygenated ground waters after a flow has been covered by others and thus protected from direct atmospheric oxidation, and the action of oxidizing mineralizing solutions such as those believed by Pumpelly to have both deposited the copper and oxidized the ferrous Iron minerals.

The activity of oxygenated waters is so closely related to ordinary weathering that it must be, in large measure, credited or discredited on the evidence regarding that process, which is discussed below and rejected.

Pumpelly's ideas of the nature and source of the solutions that carried the copper and of the reactions, by which the metal was deposited are discussed fully under "Ore deposits" (p. 120) and are regarded as not in accord with the facts now available. That argument need not be anticipated here, but the following general considerations may be mentioned as controverting the close relation assumed by Pumpelly to exist between oxidation of iron and deposition of copper.

1. The oxidation is no more marked in one part of the series than in another. A flow in the upper part of the series, thousands of feet stratigraphically above the flows carrying copper in commercial quantities, is as well oxidized as one of similar texture carrying minable copper.

2. In a given lava top—for example, that which contains the Osceola lode—the degree of oxidation is the same where it is minable as it is miles distant, where it is barren.

3. The western lavas, which show no evidence of the action of mineralizing solutions, such as vesicle filling, display the same features of oxidation as the flows in the Michigan copper district.

SURFACE WEATHERING IMMEDIATELY AFTER EXTRUSION

Normal weathering at the surface involves well-understood processes, both mechanical and chemical. The mechanical processes are disintegration and transportation, which together constitute erosion. The chemical processes are oxidation, hydration, and carbonation, followed by removal of the soluble compounds produced. These processes result in the formation of characteristic end products, among which are kaolin, limonite, and calcite, the development of pore space, the softening of the rock, and a textural breakdown. In general, the chemical changes are farthest advanced at the surface, decreasing and disappearing in depth. They extend outward from joints and cracks into the adjacent rock. Under the conditions that probably prevailed during the epoch of lava outflow in Michigan, the general order of weathering attack on a basic flow is glass and olivine first, followed by pyroxene, feldspar, and finally magnetite. Magnetite is very resistant, commonly remaining sufficiently unaltered to retain its strong magnetic property in a residual soil or a black sand.

The principal chemical changes characteristically shown by weathered basic rocks as compared with their fresh equivalents are these: The ratio of silica to alumina is diminished, as shown in 16 out of 17 pairs of analyses cited by Leith and Mead,[38] and the ratio of total iron to alumina either decreases or remains nearly constant. In 13 out of 15 pairs of analyses compared total iron is either lost or essentially constant relative to alumina; in the other two iron has increased.

[38]Leith, C, K., and Mead, W. J., Metamorphic geology, p. 24, 1915.

Such, then, are the outstanding chemical and physical changes which should be exhibited to a greater or less degree by the tops of basic flows if their color and their increased iron and oxygen content were occasioned by normal weathering. It can readily be shown that the Keweenawan flows do not exhibit these changes.

Most of the flows of the smooth cellular type show no evidence of disintegration. Ropy tops are preserved intact, as well as all the minute original textural details of the rock, even to the very surface. There has been no crumbling, softening, or development of pore space; there has been no slumping and therefore no considerable lateritic concentration; there is no visible relation between amount of oxidation and proximity to joints, and therefore no considerable movement of iron or oxygen by solutions can have occurred after the rocks were formed.

In the Columbia River flows, where the rock has clearly weathered to form a residual soil, the trap underneath the soil has crumbled and rotted to a great depth along the joint planes, but the greater part of any thick flow at the top of which the soil may lie is left intact. Limonitic alteration stains the rock along all joints and fractures, both on a large scale and microscopically. Yet in these Michigan flows that have the red tops the increase in ferric oxide, though at its maximum in the upper 10 to 20 feet, starts practically at the base of the flow and is nowhere seen to be related to joints and fractures. It is difficult, therefore, to ascribe the state of oxidation of the iron to weathering.

Still more difficult is it to explain the actual increase in total iron as a consequence of weathering. If simply the oxidation of the iron normally contained in the rock were involved, it would perhaps suffice to say that the glassy portions are highest in ferric iron because they are most susceptible to alteration. But they are actually higher not only in ferric but in total iron. No evidence of iron enrichment after solidification has been recognized, except such as is related to the copper mineralization, which occurred much later, and except for rare and minor coatings of specularite. No concentration of ferric iron has been found to have taken place by the filling of openings. The hematite is uniformly distributed throughout the devitrified groundmass, in which the most minute textures have been preserved.

The downward decrease of the ferric oxide is not obviously incompatible with weathering, but the distribution of total iron is not to be explained by weathering. It increases toward the top and to a slight extent toward the bottom of the flow. Detailed study of the distribution of the ferric iron reveals other features difficult of explanation by weathering. For example, on the Osceola and Isle Royale lodes there are not uncommonly stretches of dense trappy material in the midst of the fragmental material that divide it into an upper and a lower portion. It would be natural to expect that weathering would be somewhat less intense below this relatively impermeable trap than above it, but no difference can be detected; both upper and lower layers are iron-rich and highly oxidized. Large areas of the Kearsarge lode are covered by one or more nonfragmental flows of local extent which are possessed of characteristics so like the Kearsarge that they are regarded as probably small surface gushes from the Kearsarge flow itself. The Kearsarge lode is as well oxidized below these gushes as elsewhere. A similar condition is present on the Baltic flow. If weathering has been effective in producing ferric oxide, it either must

have worked with surprising rapidity before the gushes covered the main flows, or else it has shown a surprising preference for action on the main flows. Especially difficult is it to explain the increase in total iron content in the Kearsarge amygdaloid where covered by these gushes. The extra iron can not have come from lateritic concentration of the Kearsarge flow, for that is precluded by the evidence already adduced, and moreover none of the amygdaloid below the gushes had opportunity to be removed. Nor can it have been derived from the overlying gushes, for they have not been leached.

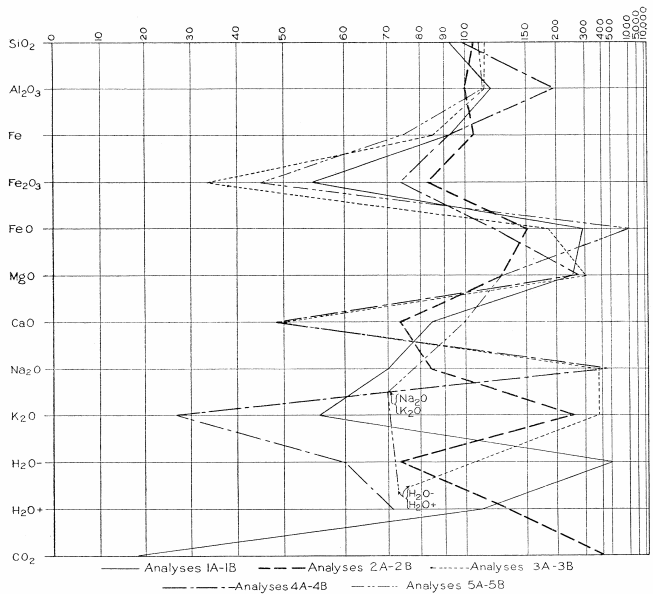


FIGURE 5.—Gains and losses in constituents in oxidized tops as compared with trap portions of flows. (See analyses, p. 37.) Points on the diagram are obtained by dividing the percentage of each constituent in the trap by the percentage of the same constituent in the amygdaloidal top of that trap, and multiplying the quotient by 100. The points then indicate for each constituent the number of grams of amygdaloid required to furnish the amount of that constituent present in 100 grams of the equivalent trap. Thus the diagram shows that there is as much Fe_2O_3 in 35 to 85 grams of amygdaloid (according to which pair of analyses is chosen) as there is in 100 grams of the corresponding trap. Assuming any constituent as constant, all points for other constituents to the right indicate a loss, and to the left a gain. Thus assuming SiO_2 or Al_2O_3 to have remained constant in the change from trap material to amygdaloid, Fe_2O_3 and CaO have been added and FeO and MgO have been lost. (Leith and Mead, Metamorphic geology, p. 288, New York, 1915)

The chemical changes involved in weathering are not those which distinguished the red tops from the deeper portions of the flow. The chemical criteria must, indeed, be used with caution, because the analyses show the composition of the tops of the Michigan flows after they have undergone several periods of alteration and mineralization and the changes due to each period are not readily separated. Two of the changes found to be characteristic in the weathering of basic igneous rocks have been pointed out.

In the five pairs of analyses (see p. 37 and fig. 5) available for the comparison of oxidized tops and deeper traps silica is constant or has gained relative to alumina. In four out of the five total iron has gained relative to alumina; in the fifth pair the iron-alumina ratio is about constant, in spite of the fact that the specimen that represents the top of the flow in this pair was taken from the lower part of a nonfragmental amygdaloid, which is always lower in iron than the upper part.

The later mineralizing processes have apparently exerted little effect on the silica-alumina ratios. The traps themselves contain about 46 per cent SiO_2 and 17 per cent Al_2O_3. The chief minerals added to the tops of the flows that would affect the SiO_2-Al_2O_3 ratio are epidote, pumpellyite, chlorite, and quartz. The first three of these have less silica and more alumina than the trap ratio; the quartz, of course, would increase the silica, but it is probably not present in a proportion sufficient to exceed the silica deficiency of the other three. The introduction of epidote, pumpellyite, and chlorite would cause a loss of iron in the tops of flows relative to alumina and hence would accentuate and effects of weathering. The fact, then, that the red tops, as compared with their corresponding traps, show a gain of both silica and total iron relative to alumina, in spite of opposing tendencies introduced by the later mineralization, argues against weathering.

By the evidence of structure, texture, and distribution of ferric oxide, therefore, the weathering hypothesis appears to be eliminated. The mineralogic evidence points to the same conclusion. Weathering of basalts, as in the Columbia River lava field, has yielded kaolinic and limonitic soil but has left much of the magnetite unoxidized. In the red tops of the Michigan and Idaho flows there is neither kaolin nor limonite; the feldspars, not withstanding their minute size and intimate contact with hematite, are strikingly fresh, but the magnetite is altered almost completely. In Michigan the magnetite has in many places been changed to hematite throughout the thickness of the flow. In the basalts of Idaho and in those of Washington that have not been affected by recent weathering the alteration of the magnetite is more closely confined to the upper parts of the flows, where the content of ferric iron is highest.

HYDROTHERMAL ALTERATION

Alteration of rocks by hot solutions emanating from an igneous mass is a common phenomenon; a lava flow, therefore, might conceivably be altered by solutions derived from a later flow with which it is in intimate contact. No proof has been found, however, that such action has occurred to an appreciable degree in the Michigan lavas, and this agency could not possibly explain the differences which the top and the bottom of a given flow exhibit. Downward passage of solutions from a liquid flow to the cooled flow beneath it would, moreover, be greatly impeded by the thin chilled skin, which, as already shown, was usually rolled under the advancing flow or quickly formed at the bottom.

A modification of this idea is that the altering solution did not come entirely from the overlying flow but was afforded by moisture and air present in the permeable top of the underlying flow and entrapped there by the outpouring of the next flow. The resulting steam and hot air might cause some oxidation, but it seems unlikely that the permeable top would originally hold enough oxygen as air to equal the amount present in excess ferric iron; and as for iron concentration, it is evident that nothing could be accomplished by such a process, unless it left a correspondingly iron-leached mass or unless the iron-robbed material was removed by solution—neither of which has happened.

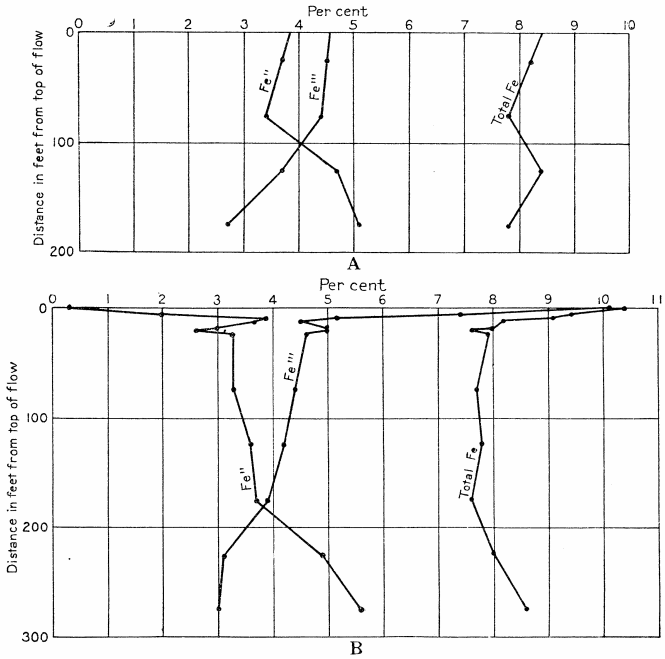


FIGURE 6.—Change in character and content of iron in different parts of lava flows. A, Smooth-top flow; B, breccia-top flow

Under either form of the hypothesis, it would seem that a basalt flow which was able to force oxygen downward for scores of feet into the amygdaloid, and even into the trap, of the underlying flow, ought to produce some perceptible effect on the top of an underlying felsite conglomerate, even though the felsite was already almost completely oxidized and though felsite is a more stable rock than basalt. Yet the tops of felsite conglomerates that are directly overlain by basalt nowhere show any special oxidation or any other change that can be ascribed to the action of the lava. Nor are the amygdaloidal conglomerates more thoroughly oxidized where they are in direct contact with the next overlying flow than where they are separated from it by a bed of felsitic conglomerate. This hypothesis, therefore, seems to receive no support from field observation.

ATMOSPHERIC OXIDATION OF HOT TOPS

There is much to commend the idea that the lava tops have undergone very rapid surface oxidation while they were exposed to the atmosphere in a highly heated condition.[39] This process might account for the production of hematite instead of limonite, and for the freshness of the feldspar microlites and the survival of the delicate texture of the rock.

Study of the cold and the hot parts of dumps of basic slags shows that a thin film of hematite-red is produced on the very surface of the slag, mainly before it cools below red heat; but fractures that have opened in the solidified but still very hot black slag after some apparently critical temperature has been passed remain black and unoxidized; also where drops and thin sheets of the molten slag are formed by the splashes or spatters and chill suddenly they solidify jet-black without undergoing perceptible oxidation. These dark slags, exposed to weathering in both northern and southern climates, undergo less change during many years than they experienced in five or ten minutes when at or just below red heat. Many slags, however, do not become oxidized and reddened at the surface, even while hot. The reason for this difference in behavior is not apparent.

If on a shallow layer of slag solidifying as a compact glass and losing its heat very quickly a thin red film will form in a few minutes, it is possible that a thick lava flow, which would remain hot for a much longer time, might abstract so much oxygen from the air as to become considerably oxidized well down into its vesicular top; and the depth of oxidation would be still greater if the top were brecciated. Jaggar, indeed, believes that air is carried down by convection from the surface to the deeper portions of the flow, where it combines rapidly with the ferrous iron of the lava.

But such action, while it may and probably does account for some of the oxidation of the tops and perhaps might cause a little oxygen to penetrate deeply into the lava that solidified as trap, could not aid in the concentration of iron toward the flow surfaces. This hot oxidation might have helped to raise the oxygen content of the flow tops, but some other process must have produced the main features of iron and oxygen distribution.

[39]Russell, I. C., A reconnaissance in southeastern Washington: U. S. Geol. Survey Water-Supply Paper 4, p. 43, 1897. Jaggar, T. A., Seismol. Soc. America Bull., vol. 10, p. 155, 1920.

MAGMATIC PROCESSES

The remaining possible causes of those listed on page 38 relate to the behavior of molten magma and are so closely allied that a choice between them is neither easy nor positive.

Magmatic segregation.—The quickly chilled tops and bottoms of flows are supposed to have solidified before differentiation had made pronounced changes and therefore to represent closely the composition of the original magma. Within the flow, where solidification by crystallizing proceeded more slowly, sinking of heavy crystals has, in numerous examples, produced a concentration of the ferromagnesian constituents toward the base, leaving the upper portion less basic, and floating of lighter crystals has increased this effect.[40]

That gravitative differentiation has operated is indicated by occurrences like the zone filled with feldspar crystals just under the amygdaloid portion of the Kearsarge flow, in which the crystals have evidently moved upward from deeper in the flow; and the increase in total and in ferrous iron which some of the flows show in their lower third, as compared with the middle, is consistent with slight increase in magnetite, olivine, and pyroxene toward the base. Rising and sinking of crystals, however, does not account for deep oxidation and does not explain the concentration of either iron or oxygen in the flow tops.

Fumarolic alteration.—It is well established that a crystallizing magma gives off gases which may attack not only older adjacent rocks but also the earlier solidified portions of the magma itself. In active volcanic regions the lava bordering fumarolic vents is conspicuously altered by the heated gases that emanate from the underlying, still fluid magma.

It is known, in particular, that ferrous iron may be oxidized by fumarolic action.[41] One example that has been described by Diller[42] and observed by Mr. Broderick occurs in the flow of the Cinder Cone, near Mount Lassen, Calif. As shown by Diller, the Cinder Cone itself was formed about 200 years ago, but the nearby flow of black quartz basalt was poured out somewhat later. The flow came out into a small lake and is of the aa type, exceedingly rough and difficult to walk upon. It contains many great blocks of black lava that are reddened on some portion of their surface, which may be the top, the bottom, or any side; and it is strewn with many little heaps of loosely cemented brilliant-red vesicular fragments. Along part of the rim of the deep crater at the top of the Cinder Cone the exposed surfaces of lava fragments are colored bright orange and red. The distribution of all these colorations of the rock shows clearly that they are related to fumarolic action.

[40]Daly, R. A., Igneous rocks and their origin, p. 450, 1914. Bowen, N. L., The late stages of the evolution of igneous rocks: Jour. Geology, vol. 23, No. 8, suppl., 1915.

[41]Gautier, Armand, Compt. Rend, vol. 132, pp. 61, 189, 932, 1901; vol. 136, p. 16, 1903.

[42]Diller, J. S., A late volcanic eruption in northern California: U. S. Geol. Survey Bull. 79, 1891.

Thin and polished sections of this reddened basalt greatly resemble some that were cut from the fine-grained iron-rich parts of breccias in the Keweenawan series. In the recent as in the ancient lava fresh microlites of feldspar and crystals of olivine partly or wholly altered to hematite are embedded in a glassy matrix crowded with minute particles of hematite, the abundance of which accounts for the red color and for the high proportion of ferric iron found by chemical analysis. The black vesicular basalt of Cinder Cone contains 4.30 per cent of iron in the ferrous state and 1.51 per cent of iron in the ferric state, a total of 5.81 per cent. The reddened equivalent, altered by hot gases, contains virtually the same amount of total iron, 5.85 per cent, but only 0.79 per cent of this is in the ferrous state, 5.07 per cent being in the ferric state. This, then, is a case of simple oxidation by fumarolic action of iron already present in the rock. What the oxidizing agent was is not known; it may have been steam or some more vigorously oxidizing gas, or it may have been atmospheric oxygen affecting the rock where hot gases kept it heated for a longer time than elsewhere.

Thus, at Cinder Cone fumarolic action is a factor, direct or indirect, in locally oxidizing the iron of basalt without altering its amount, and the resulting rock is much like that in many of the red tops of the Michigan basalts. It may next be inquired whether or not fumarolic action, or any action of volcanic gases, can account not only for the oxidation of iron but for that increase in quantity of iron which has occurred in flow tops like the Kearsarge amygdaloid. This increase is not merely a relative one, such as would be accomplished by a partial removal of some other constituents, for, as already emphasized, there is no evidence that such removal has occurred. There has been an actual addition of iron, and this iron has been introduced into the solid glassy part of the rock without filling the vesicular cavities.

The deposition of ferric compounds, including hematite and ferric chloride, around fumaroles has often been observed.[43] Whether or not such additions of ferric iron could be incorporated into the rock matter itself is a question on which there is no evidence available. Even if it is granted, however, that typical fumaroles could produce a thorough permeation of the rock by ferric oxide around local vents, it is not easy to understand how they could affect to a marked and fairly uniform degree the tops of scores of superposed flows. In the brecciated tops that were continuously broken as the flow was in progress gases might rise at all points through the top from the underlying lava. In the smooth tops it would be expected that the gases would escape through more localized vents, but no such vents have been recognized. Any such action is closely akin to the action from the gases of the flows before solidification that is discussed in the following section.

[43]Clarke, F. W., The data of geochemistry, 5th ed.: U. S. Geol. Survey Bull. 770, pp. 261 et seq., 1924. Allen, E. T., Chemical aspects of volcanism: Franklin Inst. Jour., vol. 193,'p. 34, 1922.

Fumarolic action in the strict sense then, although it may accomplish both the oxidation and the deposition of iron around local vents, could not affect the widespread, continuous, and deeply penetrating oxidation seen in the Michigan flows.

Action of gases from the flows.—There remains to be considered the action of gases given off from the flow itself before solidification and acting on the melt and on the gathering crust as they ascended. That gas rising from the lower parts of the Michigan flows was abundant in the upper parts while they were still fluid is shown by the profusion of vesicles. How much more gas was liberated before the viscosity became sufficient to imprison it as bubbles is not known, but it may well be that in both, the smooth-top and the brecciated-top flows the gas represented by vesicles is the smaller part of the

total. Nearly all observers of flowing lava refer to the great volumes of steam and other gases given off from its top. Silvestri,[44] for example, who investigated volcanic gases at Etna, says: "The fresh, still flowing lava acts like one great fumarole and emits from its surface white fumes." Other examples of the high gas content are cited in the discussion of the lava flows on page 32.

The effects of these gases, if they produced any effects, must have been similar in distribution to the observed oxidation and iron enrichment. As the chief direction of escape of the gases is upward toward the surface, the lower part of the flow will come into contact with only the gas that it held, but the uppermost part, so long as it remains liquid, will be traversed not only by its own gas but by nearly all that is liberated from the parts of the melt lower down. Furthermore, the upper part, as it becomes viscous and tends to slacken its rate of flow compared with the more fluid material deeper down, will receive the gas not only from the portions originally below it but also from those new portions that flow underneath it. If, then, a given portion of lava is changed chemically in proportion to the quantity of gas that passes through it, the chemical effect of the gas should be least near the bottom of the flow and greatest near the top. The distribution of hematite is thus in striking harmony with the hypothesis that it was formed through the agency of gas liberated from the flow as it gradually cooled.

[44]Cited by Clarke, F. W., U. S. Geol. Survey Bull. 770, p. 266, 1924.

The hypothesis receives further support from the distribution of the hematite as seem under the microscope. The particles of hematite form a pattern that seems characteristically igneous. They are not deposited in the vesicles nor included in the feldspar microlites but are crowded around both, as if pushed aside by or attracted to the growing crystals and expanding bubbles. All this suggests that the hematite was formed before the solidification of the rock and is not a product of later alteration by fumaroles or otherwise.

The chemical composition of the gases whose action on the Keweenawan flows is so strongly suggested can only be conjectured. Information regarding the gases even of modern lavas is not abundant, but there is evidence that they may contain both a volatile compound of iron and an oxidizing agent.

The emanations from some of the lavas of Etna contained ferric chloride, though those from others did not. Iron oxide was deposited by fumaroles in the Valley of Ten Thousand Smokes, Alaska,[45] and many other instances could be cited. Emanations from intrusive magmas, again, have in many places deposited not only magnetite but hematite in large quantity. The iron is supposed by some to have been expelled in the form of ferric chloride. It is therefore reasonable to suppose that the gases of the lavas contained some volatile compound of ferric iron, together with agents capable of oxidizing the iron already in the flow".

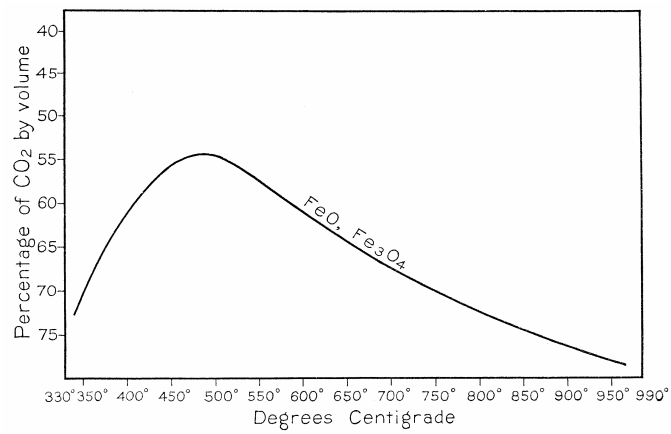


FIGURE 7.—Stability relation for the equation $Fe_3O_4 + CO \rightleftarrows 2FeO + CO_2$. (After Findlay)

If the iron was conveyed upward as volatilized ferric chloride, its fixation as hematite may have been aided, if not mainly accomplished, by atmospheric oxygen, which would doubtless be very active at certain temperatures. Jaggar[46] believes that its action may penetrate deeply under certain conditions.

Few data are available regarding the gases given off from these old flows. It is of interest, nevertheless, to consider some possible or probable reactions, though it must be recognized that the actual reactions were much more complex. The following is possibly the simplest condition.

[45]Zies, E. G., The fumarolic incrustations in the Valley of Ten Thousand Smokes: Nat. Geog. Soc. Contr. Technical Papers, vol. 1, No. 3, 1924.

[46]Jaggar, T. A., jr., Seismol. Soc. America Bull., vol. 10, p. 155, 1920.

Steam or water vapor is the most abundant gas given off by cooling lavas, and next in amount is carbon dioxide. Day and Shepherd found the gases from Kilauea to consist largely of water and the dried gases to contain from about 24 to 74 per cent of CO_2, most of them 60 per cent or more, and 3.5 to 5.6 per cent of CO. The temperature of basaltic lavas on issuing is probably above 1,000° C. We may consider, then, the probable reaction of these two most abundant gases during the cooling of the flows. For the equation

$$3FeO + H_2O \rightleftarrows H_2 + Fe_3O_4$$

Eastman and Evans[47] have shown that from 675° to 1,000° C. the hydrogen in the mixture ranges from 46 to 9.9 per cent by volume—that is, at the higher temperature there was little tendency to the oxidation of ferrous iron, but at the lower temperature such oxidation was pronounced.

Day and Shepherd[48] have shown that at 1,100° C. water is essentially neutral to powdered basaltic rock. There are no published data on the reaction of water and ferrous iron below 675° C, but Shepherd[49] states

oxygen, and iron, which has been discussed by that at and below 600° C. steam has a strongly oxidizing effect upon ferrous iron.

Much is known of the chemical system carbon, Findlay.[50] The stability relations of most interest in the present discussion are those of CO_2, CO, FeO, and Fe_2O_3. Figure 7 gives the stability relation for the equation $Fe_3O_4+CO_4 \rightleftarrows 3FeO + CO_2$. The temperature most favorable for the movement of the reaction to the left is 490°; at 1,000° the tendency is strongly to movement to the right.

It would appear, then, that when the lavas issued and until they had reached a temperature below 1,000° the tendency for H_2O or CO_2 to oxidize FeO would not be marked. As the temperature decreased, however, this tendency would increase to a maximum at 490° for CO_2 and a maximum at some undetermined temperature, probably below 600°, for H_2O, or a point at which the tops would have been solidified or very viscous. The tops of the flows would reach the oxidizing temperature for FeO soonest and would doubtless be held at a favorable temperature as long as large volumes of gas were passing through them, so that in respect to temperature and quantity of gas passing through them the tops are most favorably situated for a relatively long period and consequently high degree of oxidation. Any rainfall on the surface of the flows while they were still hot would act as an oxidizing agent, so that this may have been an additional factor in the high oxidation of the top, as well as contact with the oxygen of the air.

[47]Eastman, E. D., and Evans, R. M., Equilibria involving the oxides of iron: Am. Chem. Soc. Jour., vol. 46, p. 888, 1924.

[48]Day, A. L., and Shepherd, E. S., Water and volcanic activity: Geol. Soc America Bull., vol. 24, p. 603, 1913.

[49]Shepherd, E. S., oral communication.

[50]Findlay, Alexander, The phase rule and its applications ,5th ed., p. 248, 1923.

As set forth in the section on formation of lava tops the smooth tops occur on flows that issued with a low gas content and the rough fragmental tops on flows that issued with a high gas content. It is a reasonable assumption that the high oxidation of the breccia tops is due to their relatively high gas content and that the relatively slight oxidation of the smooth-top flows is due to low gas content.

This long discussion, then, leads to the general conclusion that, although the oxidation of the iron in the flows may have been due to several agencies, it was effected in dominant part by the action of the gases given off by the lava itself; and it is regarded as probable that the gases most active in the process were H_2O and CO_2.

COPPER CONTENT OF THE BASALTS

The literature holds many references to the presence of copper in fresh basic rocks, both intrusive and extrusive. The analyses of basalts, diabases, and gabbros compiled by Washington[51] show that copper was determined in few, but in the eleven analyses in which copper was determined it was reported in quantities ranging from a trace to 0.94 per cent of CuO. The average of these is 0.27 per cent of CuO, or 0.22 per cent of Cu. As shown beyond, this amount is five or six times that of the copper found in fresh traps from the Keweenaw an series.

Lane[52] and Grout[53] have asserted that the fresh Keweenawan basalts contain small quantities of copper as an original or pyrogenetic constituent. If the basalts contained unusual amounts for rock of this type, that fact might have, as these authors emphasize, a significant bearing on the origin of the commercial concentration of copper. Lane[54] concluded that the whole basaltic series in its present condition contains about 0.02 per cent of copper. Grout found from 0.012 to 0.029 per cent of copper in several samples of basalt that he regarded as fresh, taken from the Keweenawan of Minnesota. He also found that the freshest specimens contained the most copper and the most altered specimens (character of alteration not given) the least copper, and he inferred that copper was removed by the alteration. From microscopic work and from finding that in a partly altered rock containing 0.02 per cent of copper only one-tenth of this amount was soluble in nitric acid, Grout concluded that most of the copper is present, in the fresh rock, not as metallic copper or as sulphide but in the form of an insoluble silicate, probably associated with the abundant basic silicates of the rocks.

Morozewicz,[55] on the other hand, estimated that the basalt dikes of the Commander Islands carry copper in the fresh rock to the extent of 0.04 per cent. From tests made on several mineral constituents he concluded that the magnetite contains the copper; no copper was found in the pyroxene, and no sulphur was found in the rock.

[51]Washington, H. S., U. S. Geol. Survey Prof. Paper 99, pp. 1049-1106, 1917.

[52]Lane, A. C, Michigan Geol. Survey Pub. 6, vol. 1, pp. 175 et seq., 1911.

[53]Grout, F. F., Econ. Geology, vol. 5, pp. 473-476, 1910.

[54]Op. cit., vol. 2, p. 778.

[55]Morozewicz, J., Das Vorkommen von gediegenem Kupfer auf den Komandor-Inseln: Com, géol. Mém., new ser., livr. 72, pp. 45-88, 1912.

In the course of the present examination, an independent estimate of the copper present in the Michigan basalts was made. About 20 pieces of drill core, each representing the freshest-appearing trap obtainable, were taken from drill holes on the Cliff, LaSalle, Seneca, Ahmeek, and Osceola properties. All of them were combined into a composite sample, which was analyzed for copper soluble in nitric acid, for total copper by fusion, and for sulphur. The purpose of determining copper after fusion and sulphur was to ascertain the total copper present and gain an idea of its state of combination. If more copper were obtained by fusion than by solution in nitric acid, the fact would lend

support to the commonly held views that copper was present in the silicates as copper silicate, or in magnetite as an oxide.

Similarly, a composite sample was made, from the same drill cores, of trap that looked altered or was fissured and chloritized but that contained no copper visible to the naked eye, and a third sample consisting of amygdaloids, which likewise held no visible copper. The reason for making these two composites was that Lane had included materials of these kinds in the samples from which he estimated the average copper content of the traps, and it was thought that his inclusion of amygdaloids and of altered and fissured trap probably gave him a higher average copper content than would have been obtained from the freshest traps alone. The composite samples were assayed by W. J. Hillenbrand, of the Calumet & Hecla Co., with the following results, which are subject to an error of about 0.02 per cent.

Copper and sulphur in composite samples of trap and amygdaloid

	Copper soluble in nitric acid	Copper by fusion	Sulphur
Fresh trap	0. 040	0. 048	0. 012
Altered and fissured trap	. 036	. 034	. 021
Amygdaloid	. 032	. 032	. 014

Thus, the freshest obtainable traps of the district contain a few hundredths of 1 per cent of copper. The quantity is greater than that found by Lane and by Grout in the Keweenawan of Minnesota, but it is much less than that shown in analyses of similar rocks from some other localities. It was expected that the altered trap and the amygdaloids would run higher in copper, but the results show that they have about the same amount as the freshest trap.

The copper obtained by fusion is the same, within the limits of error, as the copper soluble in nitric acid, so that little, probably none of the copper is contained in insoluble silicates. Olivine is soluble in nitric acid, and if olivine were present in the rocks any copper that it contained would be soluble in acid. However, the olivine is practically all altered, and whether or not its alteration product, serpentine, would yield any copper it might contain to a nitric acid solution is not known. Sulphur is present in small amounts, more than enough to combine with all the copper as chalcocite but not so much as would be present if the copper occurred in chalcopyrite alone. The analyses suggest, therefore, that the copper is probably not present as silicate but that it may be present in part as sulphide and in part in some other state of combination or as native copper, or wholly as chalcocite, or as chalcocite and chalcopyrite together.

Polished sections of the duplicates of the trap samples included in the composite sample show under the microscope that copper is present in, tiny rounded specks of native metal and chalcopyrite. Native copper is more abundant than the sulphide. In some sections both are present, but most contain only the one or the other. Specimens of the Greenstone flow (none of which was included in the composite sample) show native copper, chalcopyrite, and probably chalcocite. Although microscopic estimation of amounts so minute can not be quantitative, the definite copper minerals seen appear to be present in the proper order of abundance to account for all the copper indicated by the analyses, and it is probable that all or very nearly all of the copper is present as native metal or sulphides.

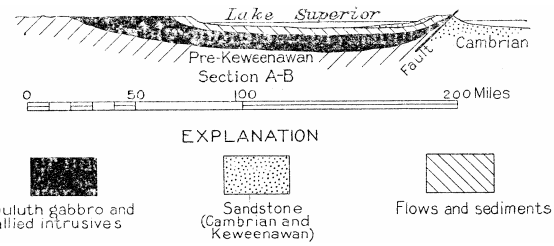


FIGURE 8.—Geologic section from Vermilion Lake, Minn., to Calumet, Mich., showing probable extent of Duluth laccolith beneath Lake Superior basin. (See pls. 1 and 3 for areal geology.)

Is the copper in the basalts primary, or has it been introduced after the rocks were formed? If the Keweenawan lavas came from the same general magmatic source as that from which the copper of the ore deposits was subsequently drawn, it would seem reasonable to suppose that they would contain a little primary copper; on the other hand, all the rocks have suffered more or less alteration, and some copper may have been introduced into even the least altered.

The facts from which conclusions are to be drawn are these: (*a*) The freshest traps that can be obtained contain only minute quantities of copper. The available analyses of rocks of the same family from other localities show on the average six times as much copper as the Michigan basalts; (*b*) these freshest traps, however, have been somewhat altered; (*c*) the freshest traps, the fissured and altered traps, and the amygdaloids, when all are carefully selected to show no copper to the eye, contain substantially equal quantities of copper, within the limits of analytical error; (*d*) analyses show the presence of sulphur and suggest but do not positively prove that the copper is not present as silicate or oxide; (*e*) microscopic examination of polished sections taken from the same small pieces as were analyzed chemically reveals the presence of minute particles of native copper and copper sulphide throughout even the freshest trap.

From these facts the following more or less tentative deductions may be made: (*a*) The presumption is strong that these definite copper minerals contain all the copper which the analyses show; (*b*) the presumption is also strong that part at least of these copper minerals are primary constituents of the trap; (*c*) it is possible or even probable that some of the copper was introduced by mineralizing solutions.

In the coarse pegmatitic or doleritic lenses that are common in some of the thick flows both native copper and copper sulphide occur in intimate association with

the rock minerals as well as with calcite and locally with prehnite. It seems most likely that all these minerals are primary to the pegmatite, which evidently resulted from a differentiation of the lava during cooling.

INTRUSIVE ROCKS

GENERAL FEATURES

Throughout the district intrusive rocks occur in the lower part of the series, near the Keweenaw fault. (See fig. 8.) To the south, at Porcupine Mountain, and north of Lake Gogebic they are present in the middle and upper part of the series also. These intrusive rocks comprise gabbro and "gabbro aplite" similar to the gabbro and red rock of the Duluth laccolith or lopolith; quartz porphyry and felsite, which are regarded as probably the fine-grained equivalents of the Duluth red rock; and dark chloritized basic dikes, which are present north of Lake Gogebic. These rocks have been intruded in masses of various form; a stock occurs at Mount Bohemia and probably some of the bodies near the Wisconsin boundary also are stocks; the Mount Houghton intrusive body and some bodies north of Lake Gogebic appear to be sills or laccoliths; and dikes occur at many places toward the Wisconsin boundary and very rarely in the northern portion of the district.

The similarity of the rocks to the Duluth gabbro and red rock series and their occurrence near the base of the Keweenawan and along the great Keweenaw fault has led to the belief that they are a part of the Duluth laccolith, which crops out in a similar relation on the north side of the basin and probably extends beneath the basin, as is more fully discussed under "Structure" (p. 50).[56]

[56]Van Hise, C. R., and Leith, C. K., op. cit., pp. 377-378. Grout, F. F., The lopolith, an igneous form exemplified by the Duluth gabbro: Am. Jour. Sci., 4th ser., vol. 46, pp. 516-522, 1918.

Rocks of the gabbro and red rock type occur at Mount Bohemia and near the Michigan-Wisconsin boundary, where relatively large bodies are surrounded by zones showing pronounced rock alteration. Diamond drilling at the Indiana mine also encountered gabbro.

The gabbro of Mount Bohemia is a dark gray-red granitoid rock of variable though typically medium grain. Its essential minerals are plagioclase, pyroxene, and magnetite in roughly equal amounts. Accessory minerals are hornblende, apatite, quartz, titanite, and sulphides. The pyroxene is partly altered to hornblende and chlorite, and the feldspar to sericite and chlorite. Leucoxene occurs as an alteration product of titaniferous magnetite. This rock has been described by Wright[57] and called oligoclase gabbro.

The associated red rock or gabbro aplite is a coarser-textured rock composed essentially of oligoclase-albite and quartz with subordinate orthoclase, magnetite, apatite, titanite and zircon. It occurs as dikes and as a stock in the gabbro and adjacent rocks.

The following analyses, taken from Lane's report,[58] show the chemical composition of these and allied intrusive rocks:

QUARTZ PORPHYRY AND FELSITE

Bodies of quartz porphyry and felsite are present at several places near the Keweenaw fault. The larger known bodies near the fault from north to south are at Fish Cove, Bare Hills, and Mount Houghton, south of Cliff, south of Ahmeek, east of Calumet, and at the Indiana mine. North of Lake Gogebic are some large masses of quartz porphyry that are probably intrusive. At several of the localities there is no clear evidence of the relation of these masses to the flows and sediments, but where the relation is obvious they are intrusive into these rocks. The fine felsite may show distinct flow structure in bodies that are known to be intrusive, as is common for rocks as siliceous and fine textured as these. The "Chippewa" felsite and the felsite of Porcupine Mountain are similar to those just described but have been regarded by geologists who have given most study to them as flows. There is also a similar rock at the Bear Lake prospect, west of Calumet, which has the appearance of a rhyolite flow but may be intrusive. This is in the Freda sandstone and is stratigraphically the highest known occurrence of felsite.

[57]Wright, F. E., The intrusive rocks of Mount Bohemia, Mich.: Michigan Geol. Survey Rept. for 1908, pp. 363-370, 1909.

[58]Lane, A. C, Michigan Geol. Survey Pub. 6 (Geol. ser. 4), vol. 1, pp. 106-109, 1911.

The rocks vary considerably in texture in different bodies and also in a single body. In the coarser varieties phenocrysts of quartz and feldspar 2 or 3 millimeters in diameter are present rather abundantly. These are inclosed in a felsitic groundmass of quartz and feldspar. The finer varieties are typical felsites, in which phenocrysts are either small and scarce or altogether absent. Dark minerals are characteristically absent from these rocks, but practically all have a reddish color due to the presence of countless dustlike particles of hematite, which appears to be an original constituent. All these rocks, as well as the pebbles of similar felsites and quartz porphyries in the conglomerates, are rich in ferric iron. The chemical composition of the Mount Houghton mass is shown in the analyses given above. The other bodies are apparently of similar composition.

BASIC DIKES

Very few basic dikes have been noted in the part of the district that has been most studied. A few examples of probable dikes were seen in the drill cores from the north end of the district. In the Onondaga drill section, north of Lake Gogebic, numerous small fine-grained green, highly chloritized dikes cut both the quartz porphyry and the lava flows. The intruded rocks for a few inches from the dike contact are considerably chloritized.

AGE OF INTRUSIVE ROCKS

There is no basis for determining the age of the intrusive rocks more definitely than as Keweenawan or post-

Keweenawan. The felsite fragments in the conglomerates closely resemble those found in place and are generally believed to have been derived from similar masses, as they are unlike any earlier rocks known in the region. If this belief is correct, felsitic intrusion, extrusion, or both must have begun early in Keweenawan time to have formed the source of the early conglomerates, and the igneous activity probably continued into late Keweenawan time, at least in the Porcupine Mountain area, where the latest known Keweenawan rocks are involved in the domical structure that is attributed to intrusion. Similar evidence of late igneous activity is afforded by the presence of a fine-grained acidic rock well up in the Freda sandstone (upper Keweenawan) near Bear Lake. Whether the intrusive rocks near the base of the series, as represented along Keweenaw Point, are early or late is not known.

STRUCTURE

The broader structural features of the Lake Superior region have been summarized by Van Hise and Leith,[59] and only such features need be set forth here as bear directly on the rocks of the copper district.

FOLDS

The dominating structural feature of the region is the Lake Superior syncline. This structural basin is roughly outlined by the present area of Lake Superior with a southwestern extension into Minnesota. West of Keweenaw Point the general strike of the axis of the basin is about N. 30° E., extending into Minnesota. East of Keweenaw Point the strike is east of south. In this direction the syncline extends to the east end of Lake Superior. Keweenaw Point is on the south limb of this syncline. The north limb is exposed on the north shore of Lake Superior and on Isle Royal. Beds that are thought to be at essentially the same horizons crop out on Keweenaw Point and on Isle Royal, about 50 miles apart across the general strike of the basin.

The syncline is asymmetrical, the beds on the south limb dipping notably more steeply than those on the north. There is a steady flattening in the dip of the beds from the base of the Keweenawan series toward the top. On Keweenaw Point the dip ranges from 80° in the lower beds to 10° at some points where the upper Keweenawan sandstones dip under the lake.

The south limb of the Lake Superior syncline is irregular in detail, being made up of a series of transverse anticlines and synclines that pitch down the dip of the main trough. (See pl. 3.) Keweenaw Point is near the crest of a northward-pitching anticline that causes the strike of the beds to change between the south and north ends from north of east, through east, to south of east. To the southwest the Keweenaw anticline merges into the Ontonagon syncline. West of the Ontonagon syncline is another anticline with its crest about at Bessemer and Ironwood. These are very broad, open folds, the distance between the adjacent crests of the Bessemer and Keweenaw anticlines being approximately 110 miles. On these large crossfolds are numerous subordinate anticlines and synclines of similar character and trend as the Allouez anticline, the Isle Royale (mine) syncline, the Baltic anticline, the Winona anticline, the Firesteel River syncline, and the Mass anticline. These also are broad, open folds but are only 5 to 10 miles across, as contrasted with 100 miles for the major cross folds. Some of the folds, such as the Allouez anticline and the Isle Royale syncline, show a rather uniform bending of the beds, with some faulting near the crest. In others, such as the Baltic and Mass anticlines, the beds are bent sharply at the crests and at the margins of the folds, but the limbs of the folds are fairly straight.

[59] Van Hise, C. R., and Leith, C. K., U. S. Geol. Survey Mon. 52, p. 620, 1911.

The domical uplift at Porcupine Mountain, also a minor fold on the south limb of the Lake Superior syncline, is 12 to 15 miles long and 4 to 6 miles wide. It has the same general trend as the Lake Superior syncline. Numerous faults are associated with this dome.

FAULTS

The Keweenaw fault, the major fault of the region, strikes in a general northeasterly direction, parallel with the Lake Superior syncline in this area. It varies in strike, however, and in general bends with the transverse northward-pitching anticlines and synclines on the south limb of the Lake Superior Basin. The fault is known from Bete Gris Bay, near the end of Keweenaw Point, where it is covered by the waters of Lake Superior, to Lake Gogebic, a distance of about 100 miles. It doubtless extends farther east under Lake Superior and may be represented to the west by faults that have been found in Wisconsin.[60] The fault is reverse or overthrust and has forced the Keweenawan rocks up and over the Jacobsville ("Eastern" or Cambrian) sandstone and thus duplicated the Keweenawan and the overlying sandstone. The rocks of the main Copper Range and the South Trap Range are believed to have been once continuous and are now separated by the Keweenaw fault. The fault dips northwest. The angle of dip is known in few places but where known ranges from 20° to 70° and in the main steepens or flattens with the dip of the overlying lavas. The rocks adjacent to the fault are much broken and displaced. In general the normal northward-dipping lava flows on the hanging-wall side of the fault are bent downward so that in places the dip is reversed, and the flat-lying sandstones on the footwall side are turned up rather abruptly. Associated with the main fault are numerous branch faults, some of which are known to diverge half a mile from the main fault, as that at the Mayflower-Old Colony mine. The flows in the block between the main fault and the branch are nearly flat-lying or have a southerly dip.

The rocks of the lava flows for several hundred feet from the fault are in most places greatly broken and

brecciated. This condition has rendered diamond drilling near the fault difficult and expensive and is the main reason wiry so little definite information regarding the attitude of the fault is available. The sandstone is less brecciated. In the following paragraphs are recorded the definite facts concerning the fault that are available:

At Bete Gris the fault can be seen under the shallow waters of the bay, but little is known of its attitude.

Southeast of Cliff a diamond-drill section shows two faults over half a mile apart, with a block of nearly horizontal flows between them.

At the Mayflower-Old Colony mine diamond drilling has shown a branch diverging from the main fault to a maximum distance of about half a mile. Between the main fault and the branch the beds are nearly horizontal or have a slight southerly dip opposite to the normal dip. The branch fault was evidently formed after there had been some movement on the main fault, as it reaches the "Eastern" sandstone in depth. The dip of the branch fault is somewhat steeper than the normal dip of the trap beds at this locality. The dip of the main fault is not known but is evidently less.

[60]Aldrich, H. R., op. cit., p. 569.

At Wall Ravine the fault is poorly exposed but seems to dip about 20°. The "Eastern" sandstone beneath and adjacent to the fault is sharply upturned, and a vertical "wall" formed by a resistant layer of the upturned "Eastern" sandstone has given the name to the ravine.

The St. Louis diamond-drill sections show the fault to dip almost parallel with the normal dip of the trap beds, about 38°, and there seems to be little disturbance of the rocks near the fault.

Where exposed at Douglass Houghton Falls the fault dips 30°-32°, a flatter angle than the normal dip of the beds. The beds near the fault, however, dip only 15°-20°.

In the Torch Lake diamond-drill section the relations are complicated by intrusion, so that the dip of the j fault is uncertain. The beds, however, flatten very much as they approach the fault.

Where exposed at Hungarian Falls the fault dips 30°-32°. The beds above the fault are relatively flat and are evidently dragged down by the fault.

At Oneco two diamond-drill holes cut the fault at depth, and its outcrop has been located fairly closely near by. The average dip of the fault is 17° between the outcrop and the nearer hole and 22° between the outcrop and the more distant hole. The beds flatten in dip toward the fault and are possibly overturned near it.

According to H. W. Fesing the trap beds exposed by the explorations near the fault along the supposed Baltic horizon in the lands of the Arcadian Consolidated Copper Co. are completely overturned and dip to the east.

Where exposed in a ravine south of Isle Royal the fault dips 56°, nearly parallel to the beds above it. There are other faults, probably related to the Keweenaw fault, within the trap series near by.

At the Atlantic prospect the fault was located at points 1,200 feet apart vertically and 300 feet horizontally; the dip, as indicated by these points, is 50°, which is somewhat flatter than the dip of the trap beds immediately above.

In the vicinity of the Indiana mine the beds near the fault are much broken and contain intrusive rocks.

At the Lake and South Lake mines there is a broad, gentle syncline and a narrow, steep anticline between the fault and the point where the rocks have the normal westerly dip. The folding that produced these features was a part of the fault movement.

The fault has been exposed at the Victoria mine, where a section of the adit shows that it dips about 70°, a little more steeply than the beds.

In addition to the Keweenaw fault and those closely associated with it already mentioned, there are many fissures near the Keweenaw fault that dip nearly parallel with or somewhat steeper than the beds. These are particularly conspicuous in the mines opened near the Keweenaw fault. On these strike fissures the movement may be scarcely noticeable or may be a few feet but is rarely large.

There are also a few reverse faults which cut the beds transversely at a somewhat higher angle, such as the Hancock and Isle Royale faults, with apparent horizontal displacements of about 600 and 175 feet, respectively, but in which the actual displacement along the direction of movement was doubtless several times as much. The Branch fissure of the Michigan (Minesota mine) may be of this class but has a relatively small displacement.

Another group that may be put in this class are faults or slips that parallel the beds. These are difficult to recognize, and it is usually impossible to determine the amount of movement on them, but there can be no doubt that faulting has occurred between the beds, especially on the conglomerate beds, which rather characteristically have on the hanging-wall side a heavy gouge that has resulted from movement. Evidently the plane surface of the conglomerates as contrasted with the rough surface of most of the flows made the top of the conglomerates a zone of easy slipping, and much of the movement during the tilting of the beds appears to have occurred on the conglomerates. L. L. Hubbard[61] has particularly emphasized faulting of this type.

There are large reverse faults around the Porcupine Mountain dome. Wright and Lane[62] show a fault extending along the entire south margin of the dome, and there is a strong reverse fault in the workings of the White Pine mine.

Near the crests of the anticlines there are numerous transverse fissures that apparently have resulted from

the bending of the rocks when the anticlines were formed. These are particularly noticeable on the Keweenaw anticline, from the North American mine to Copper Harbor, where the fissures cut the Greenstone ridge. In the straight stretch between the Allouez anticline and the beginning of the sharp curving of the Keweenaw anticline at the North American mine the Greenstone flow is massive and almost free from fissures, but it is strongly fissured around the anticline. Many of the fissures are mineralized—the Cliff, Phoenix, Copper Falls, Central, Delaware, and many others. Most of the low gaps through the Greenstone flow have also evidently been determined by fissures. Along many of the tension breaks there has been some movement, and along some it may reach tens and possibly hundreds of feet, though there are no great faults. Fissures and faults of the same character are present on some of the smaller folds, as the Allouez, Baltic, and Mass anticlines.

[61]Michigan Geol. Survey, vol. 6, p. 91, 1898.

[62]Wright, F. E., and Lane, A. C., Michigan Geol. Survey Rept. for 1908, pl. 1, 1909.

Where there is much displacement on the faults associated with the anticlines, it is commonly in a wide zone of shattering, in some extending over a hundred or even several hundred feet, as in the Allouez shatter zone, on the Allouez anticline, and the zone between the Baltic and Trimountain mines, on the Baltic anticline. Commonly where there has been much movement one or more planes in the zone show strong gouges.

The fissures and faults on the smaller anticlines are mineralized—for example, the Mass fissure and Arsenide fissure, on the Allouez anticline, and similar though less highly mineralized cross fissures on the Baltic and other anticlines.

AGE AND CAUSE OF FOLDING AND FAULTING

There is a very close relation between folding, faulting, and igneous activity in the region, and all three processes are probably different expressions resulting from a common cause.

Two general ideas have been advanced regarding the relations of folding to igneous activity. One assumes that the synclinal structure of the Lake Superior basin is the result of some phase of igneous activity. Thus Lane[63] has thought that the material of the lavas came from beneath the Lake Superior basin and that the space thus vacated was filled by the settling or slumping of the crust above. Grout[64] considers the subsidence of the roof of the Duluth gabbro laccolith or lopolith a factor in the formation of the Lake Superior syncline. Hotchkiss[65] likewise considers the origin of the syncline to be associated with the igneous activity. He pictures a great body of igneous material rising slowly through the earth's crust beneath the present Lake Superior basin. For a long period before Keweenaw an time this rising igneous mass elevated the surface above it and tilted the rock away from the present basin. The rising surface was eroded, and the material thus derived was deposited around the margin. In Keweenawan time the magma broke through to the surface as basaltic and felsitic flows. This release of pressure and transfer of material to the surface caused the crust to settle. The process of transfer and settling continued through the Keweenawan epoch, resulting in a tilting of the beds toward the axis of the basin, the earlier beds being most affected and the later ones progressively less, as outlined below.

[63]Lane, A. C., Michigan Geol. Survey Pub. 6 (Geol. ser. 4), vol, 1, p. 22, 1911.

[64]Grout, F. F., The lopolith—an igneous form exemplified, by the Duluth gabbro: Am. Jour. Sci., 4th ser.; vol. 46, pp. 516-522, 1918.

[65]Hotchkiss, W. O., The Lake Superior geosyncline: Geol. Soc. America Bull., vol. 34, pp. 667-678, 1923.

According to the second conception, orogenic movement, one phase of which was the folding of the Lake Superior syncline, is regarded as the cause rather than the effect of the igneous activity. Van Hise and Leith,[66] though not denying the possible dependence of the folding upon the extrusion of the Keweenawan basalts, believe it reasonable to assume that the dominant trend of the folds of the pre-Cambrian shield was probably established before Keweenawan time and that a thrust from the south against a continental area to the north was effective in the folding of the Lake Superior syncline.

Whichever cause was effective or predominant, the folding took place during Keweenawan time. However, it took place slowly. If Lane's correlation of flows and sediments from one side of the lake to the other is correct, erosion and deposition must have kept pace with the formation of the syncline, so that there was no considerable physiographic basin at any period, and if the material moved from the center of the basin outward, the center must have been a physiographic elevation. In both explanations the folding is presumed to have been in progress during Keweenawan time and to have been essentially completed at its end, so that late Keweenawan beds were little affected.

The domical character of the Porcupine Mountain uplift and the known presence of intrusive rocks within it strongly suggest that this fold has resulted from the intrusion of igneous material, possibly in laccolithic form. There are also outcrops of intrusive bodies near the crests of the Keweenaw anticline and the Bessemer-Ironwood anticline, and an intrusive body underlies the Allouez anticline. Some small intrusive bodies, however, such as that east of Calumet and that at the Indiana mine, are not associated with notable anticlines. On the whole there seems to be some suggestion that the transverse folds are associated with intrusive bodies, but it is not clear whether the intrusion was the cause or the effect of the folding. The transverse folds involve rocks of late Keweenawan age and were evidently formed during or after Keweenawan time.

The cause and time of formation of the Keweenaw fault are not susceptible of rigid proof with the evidence now available, as is indicated by the differences of opinion

concerning it. Van Hise and Leith regard the faulting as post-Cambrian, possibly post-Cretaceous. Lane believes that it started in Keweenawan time and continued "ages later."

[66]Van Hise, C. R., and Leith, C. K., op. cit., pp. 411, 622, 623.

It is of course clear that there has been movement since the deposition of the Jacobsville ("Eastern") sandstone. The reverse or overthrust character of the fault and the attitude of the adjacent rocks indicate that this, like many such faults, started as a fold, which broke when the elastic limit of the rocks was exceeded. The fault closely parallels the Lake Superior syncline, and the block to the north, toward the center of the syncline, was thrust upward and outward relative to the block to the south. If it is assumed that the entire Keweenawan series was laid down before the formation of the Lake Superior basin was begun, the displacement on the fault necessary to bring the Cambrian Jacobsville sandstone into contact with middle Keweenawan beds would be about 3 miles, and the relations as they exist might have been produced by combined folding and faulting, as shown in the accompanying diagram. (See fig. 9.) If, as seems likely, the Lake Superior basin was in process of formation during Keweenawan time and the fold that preceded the fault was also being formed then, the Jaeobsville sandstone was laid down unconformably on the upturned edges of the earlier Keweenawan beds and a movement on the fault of only a few thousand feet would account for the known displacement of the Jacobsville sandstone and produce the attitude of the beds adjacent to the fault as they are known and as is shown in Figure 10.

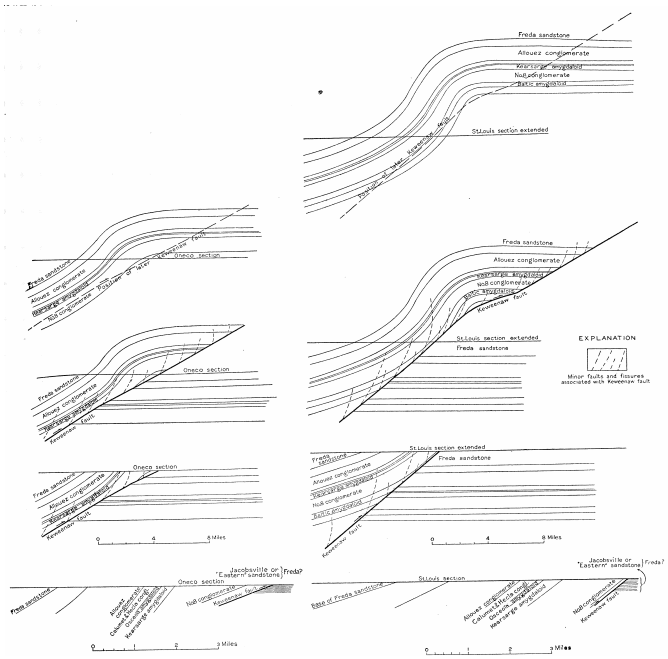


FIGURE 9.—Possible development of the Keweenaw fault and relations to beds on the assumption that the folding and faulting were both later than the deposition of the Jacobsville sandstone

Under this second assumption the movement on the fold and subsequent fault began in Keweenawan time and continued after the Jacobsville ("Eastern") sandstone was laid down, possibly for a long time after. The thrust movement from the interior of the basin suggests that the cause of the Keweenaw fault was probably closely allied to the formation of the Lake Superior syncline and the intrusion of the laccolith. It seems possible that successive upward thrusts alternating with outpouring of lava and settling during the igneous activity produced the folding and finally the faulting along the margin of the area. The faults and fissures on the anticlines and synclines are pretty clearly tension cracks produced during the folding of the rocks.

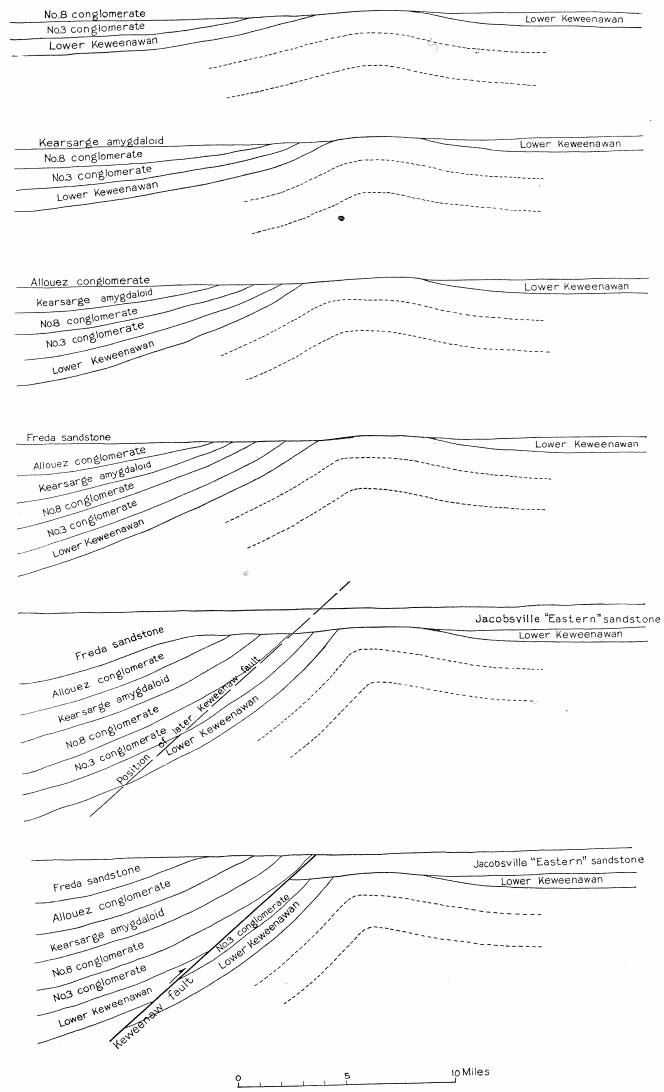
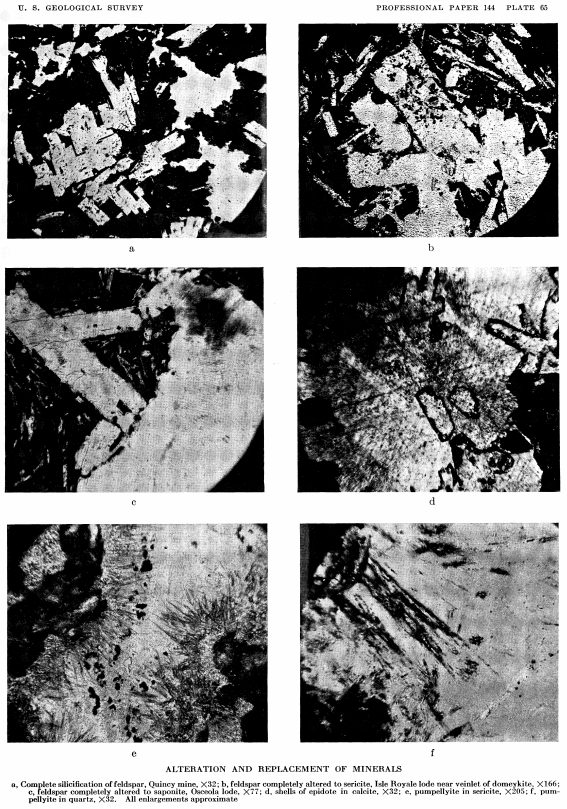
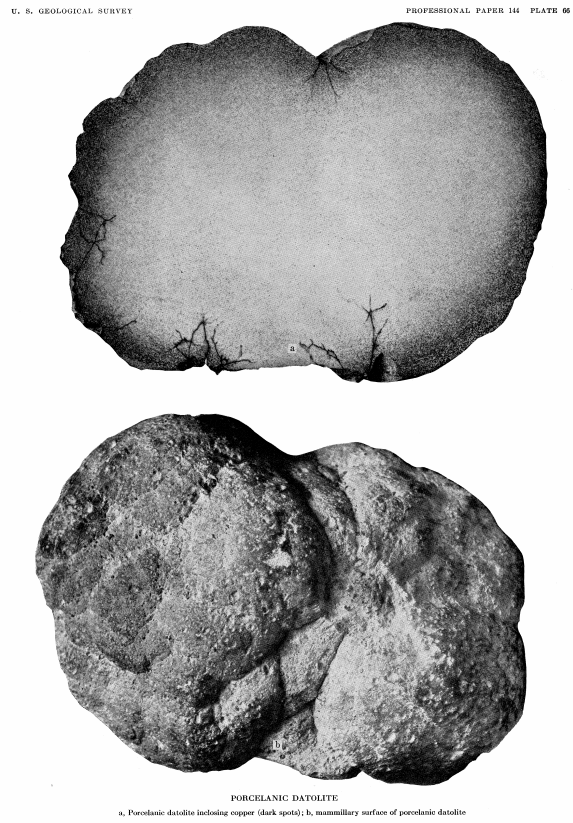


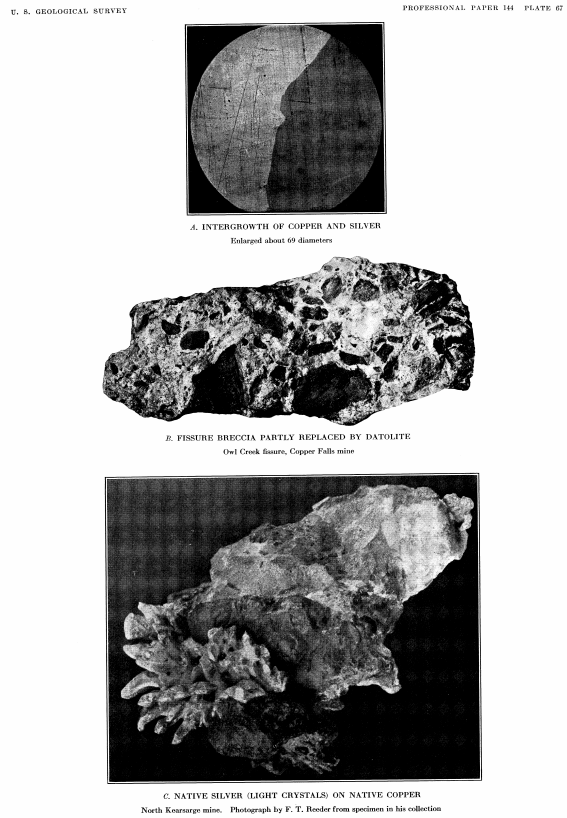
FIGURE 10.—Possible development of the Keweenaw fault on the assumption that the folding was earlier than the deposition of the Jacobsville sandstone



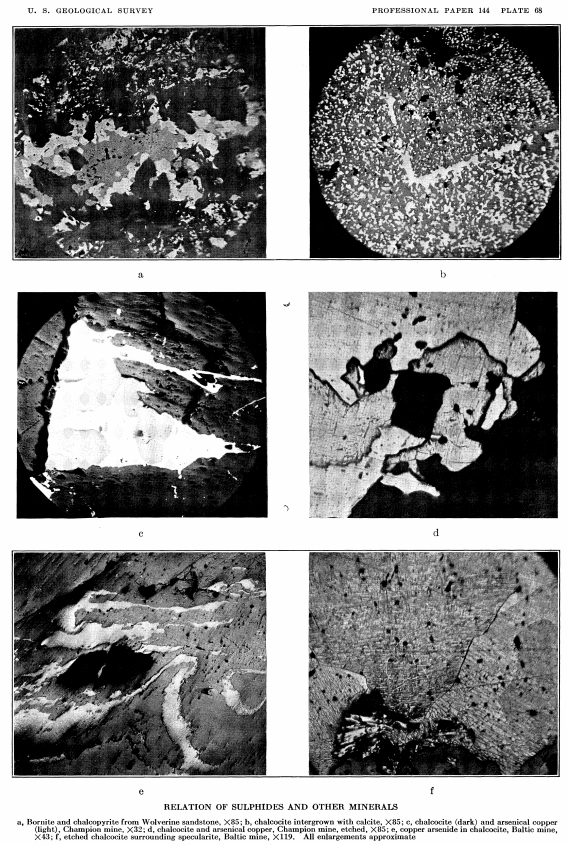
[PLATE 65. Alteration and replacement of minerals.]



[PLATE 66. *A*, Porcelanic datolite inclosing copper; *B*, Mammillary surface of porcelanic datolite.]



[PLATE 67. *A*, Intergrowth of copper and silver; *B*, Fissure breccia partly replaced by datolite; *C*, Native silver on native copper.]



[PLATE 68. Relation of sulphides and other minerals.]

MINERALOGY

The following discussion of the mineralogy is based largely on the notes of Charles Palache and Alfred Wandke. Doctor Palache made a study of the general mineralogy of the district, and Doctor Wandke did much of the microscopic work on rocks and minerals. In addition Dr. T. M. Broderick made a special study of the arsenides. The work of these men was carried on for the Calumet & Hecla Consolidated Copper Co. and has been supplemented by observations made throughout the investigation.

The minerals of the district readily fall into three main groups, based upon their periods of formation—those of the rock-forming period, those of the ore-forming period, and those of the period of weathering. (See fig. 11.)

ROCK-FORMING PERIOD

The cooling of the basaltic lava flows resulted in the crystallization of olivine, plagioclase, pyroxene, and magnetite or ilmenite, together with the formation of more or less glass. G as bubbles in the viscous lavas left open cavities or vesicles. Interstices in the ophites may also have been gas filled and later left open or filled with glass.

As the rock cooled and crystallized, it was permeated with gaseous emanations, which may have been the chief agents in producing the first alterations of the minerals or glass already formed. These changes were principally the breaking down of glass, with sotting free of dissolved minerals—hematite, pyroxene, and feldspar (in spherulitic form); the serpentinization of olivine, with or without setting free of iron oxide, mainly hematite; probably the formation of chlorite from glass of interstitial spaces or migration to fill such areas if open; and the oxidation of ferrous iron in the glass, magnetite, and silicates to hematite. It was in this period that the red tops of the lavas were formed.

During the corresponding period in the formation of felsites, quartz, feldspar, and hematite were the principal minerals to be formed. Some of the felsites were later broken up and deposited to form the conglomerates with little mineral change.

ORE-FORMING PERIOD

The main ore-forming period occurred after the rocks had been tilted to essentially their present position and broken by many fractures. They were then permeated by hot, chemically active solutions, which tended to rearrange the constituents of the rocks into new mineral combinations and also to introduce some additional constituents.

Within this period there was a broad general sequence of mineral formation, but this sequence was subject to many variations and is likely to be obscured by its own complexity. The early part of the period was characterized by the formation of the anhydrous or less hydrous minerals, such as feldspar, chlorite, and epidote; the later part by the formation of the more hydrous minerals, such as laumontite, anaicite, and saponite. (See fig. 11.) Copper was formed mainly in the intermediate part of the period.

Many of the minerals were formed along a path leading away from a source of solutions, as outward from a fissure or channelway, and minerals of one type would be forming at the advancing front of the replacement wave while minerals of another type were replacing these earlier minerals nearer the source at the same time and perhaps only a few inches away. Thus the front of the replacement wave in amygdaloid is marked by the destruction of hematite and the formation of epidote and pumpellyite, but these same minerals nearer the source of the solutions were being replaced by copper. In the iron-rich boulders in the Calumet & Hecla conglomerate the rock was chloritized at the front of the replacement wave and replaced by copper a little nearer the source, both processes evidently having been in progress at the same time and, in places, but a fraction of an inch apart.

The complexity of this period is illustrated by the relations of minerals in the Allouez shatter zone, where movement was in progress during mineralization and there was repeated opening of fissures and healing with other minerals. (See pls. 64, 65.) The general sequence of events in this zone is believed to have been as follows:

1. Fissuring occurred, and quartz and epidote were formed.

2. During the silicification of the fissure walls a little of the hematite, which antedated the fissuring, was removed.

3. As epidote developed, hematite decreased in amount, owing in part to the recombination of hematite into epidote.

4. As silicification proceeded, a little of the pulverulent ferric oxide may have recrystallized into the specular black variety.

5. A little pumpellyite was formed.

6. The early quartz-epidote mixture was shattered, and quartz, epidote, calcite, and prehnite were deposited in the fractures.

7. Prehnite partly replaced epidote, quartz, and calcite, and copper was deposited.

8. The minerals already formed were again shattered, and more calcite and quartz were deposited, together with copper.

9. Shattering was renewed, and quartz and calcite, with some laumontite, entered.

The minerals of this period both filled open cavities and replaced minerals of the rock-forming period and the earlier part of the ore-forming period. The replacement generally occurred volume for volume, but in places the altering solutions removed more than they deposited and formed cavities near the main channels, which may have

become places of deposit for later minerals. The veins were formed mainly by replacement, though there was doubtless some filling of open spaces.

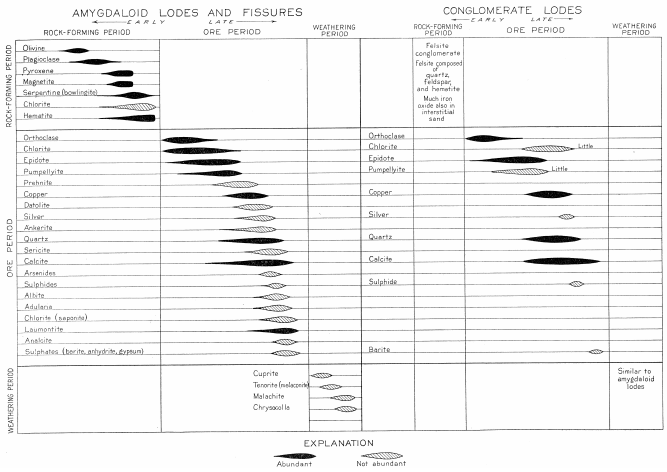


FIGURE 11.—Paragenesis of minerals of Michigan copper deposits.

PERIOD OF WEATHERING

The glaciation of the region has removed most of the products of preglacial weathering. It is only in areas protected from glacial action or areas of shattering where weathering was probably unusually deep or in association with minerals that were readily susceptible to oxidation that any notable amount of weathered material is present. In weathering native copper has generally, as is usual in other regions, been altered first to oxide and later to carbonate or silicate.

MINERALS OF THE KEWEENAWAN COPPER-BEARING ROCKS

In the following alphabetic list are included the principal known minerals of the district, and following that is a short description of the occurrence of each. In the description the minerals are grouped according to Dana's system.

Adularia.	Datolite.	Powellite.
Algodonite.	Domeykite.	Prehnite.
Analcite.	Epidote.	Pumpellyite.
Anhydrite.	Faujasite.	Pyrite.
Ankerite.	Feldspar.	Pyrolusite.
Apatite.	Fluorite.	Pyroxene.
Apophyllite.	Galena.	Quartz.
Arsenides.	Gypsum.	Rutile.
Atacamite.	Hematite.	Saponite.
Barite.	Heulandite.	Sericite.
Biotite.	Hornblende.	Serpentine.
Bornite.	Hydrocarbon.	Silver.
Bowlingite.	Ilmenite.	Specularite.
Brucite.	Kaolin.	Sphalerite.
Calcite.	Laumontite.	Stilbite.
Chalcedony.	Limonite.	Tenorite.
Chalcocite.	Magnetite.	Thomsonite.
Chalcopyrite.	Malachite.	Titanite.
Chlorastrolite.	Manganite.	Tourmaline.
Chlorite.	Natrolite.	Whitneyite.
Chrysocolla.	Olivine.	Zircon.
Copper.	Plagioclase.	Zoisite.
Cuprite.		

NATIVE METALS

Silver (Ag) occurs in varying amounts in all the lodes and fissures. Among the fissures the Cliff has probably been most productive of silver and among the lodes the Pewabic. Silver occurs in the sulphide and arsenide fissures as well as in the native copper fissures. Some of it was formed at the same time as the associated copper, though in its most conspicuous occurrences in vugs it was apparently formed slightly later than most of the copper. (See pl. 67.)

Native copper (Cu) occurs in amygdaloids, conglomerates, and fissures throughout the district. It forms masses ranging from those of microscopic size to some weighing 600 tons. Commonly it is without definite crystal outline, but in vugs it occurs in crystals and crystal aggregates, usually with rather imperfect crystal form. This crystallized copper has apparently been deposited in open spaces, without replacing other minerals. Some crystallized copper has formed in fault gouge. In the main the metal has been formed by replacement of the earlier minerals of the ore period, such as chlorite, epidote, and zoisite, as well as of the rock-forming minerals. It is very commonly intergrown with prehnite and datolite and less commonly with quartz and calcite. Most of the copper is earlier than the zeolites laumontite and analcite and earlier than saponite, adularia, barite, anhydrite, and gypsum, though a little copper has been deposited as late as any of these minerals. Where copper is associated with chalcocite in fissures either mineral may be the earlier, or the two may be contemporaneous. In the lodes the sulphide-bearing fissures are at least in part later than the copper of the lodes. The lode rock adjacent to copper is characteristically bleached by the removal and alteration of hematite, as is discussed in the section on ore deposits (p. 133).

SULPHIDES

Galena (PbS) is rare, but minute crystals of it have been noted at the Mendota diamond-drill hole No. 40 with chalcopyrite and at South Cliff with pyrite and sphalerite.

Chalcocite (Cu_2S), though formed before copper in some places, is one of the later minerals of the ore-forming period. It is of widespread occurrence in fissures cutting rocks of all kinds. It is especially conspicuous in fissures in the Baltic lode, where it occurs with ankerite, and it is also present locally in the lode itself. It is rather common in fissures in the Isle Royale lode, where it occurs with ankerite and a little specularite and where it is later than the specularite. The rock adjacent to the veins in this lode is strongly bleached. Finely divided chalcocite darkens the small calcite veins that occur in the Allouez conglomerate wherever it has been opened, and the mineral occurs similarly in several other conglomerates. In the Calumet & Hecla conglomerate it is most abundant at the Centennial shafts, north of the main ore

shoot. It is present in veins and vugs at Mount Bohemia, Calcite-chalcocite veins are plentiful in the White Pine and Carp Lake mines, and chalcocite is disseminated in part of the sandstone. In short, chalcocite is widespread but nowhere abundant, though the Baltic lodes contain veins of nearly solid chalcocite several inches wide. (See pls. 68, 69.)

Sphalerite (ZnS) is rare but is reported from a fissure at South Cliff with pyrite and galena.

Bornite (Cu_5FeS_4) in small amount accompanies the chalcocite in some of the sulphide fissures. The fissures in the Baltic lode contain bornite most abundantly, but it is present also in fissures in the Isle Royale lode. It is a common mineral in the veins and vugs in the gabbro and gabbro aplite of Mount Bohemia.

Chalcopyrite ($CuFeS_2$) is of rather rare occurrence. It is present in the veins of Mount Bohemia and was seen in drill cores near a feisite intrusive at Mendota. It occurs sparingly in veins with chalcocite in the Isle Royale and Baltic lodes and was observed in veins in quartz porphyry in the Onondaga drill cores. It is visible in some of the pegmatitic lenses in the thicker flows and is present as microscopic crystals in some of the freshest normal trap. It occurs also in the Wolverine sandstone in the Ahmeek mine.

Pyrite (FeS_2) is reported in a small fissure with sphalerite and galena at South Cliff. Pyrite is notable for its practical absence.

ARSENIDES

Arsenic, in the form of copper arsenides (pl. 71), occurs in Michigan associated with the copper in deposits of all types—amygdaloid and conglomerate lodes and fissures—but is most abundant in certain of the fissure deposits, and in the lodes it is especially localized near the arsenide fissures. The lode copper of the Baltic and Isle Royale lodes, however, is arsenical throughout and distinctly lighter in color than the arsenic-free copper. On etched surfaces the “arsenical” copper approaches in appearance some of the arsenic compounds.

Compounds of copper and arsenic.—As they occur in Michigan, the arsenides form mixtures so intimate and complex that the early investigators[67] mistook different combinations of minerals for new species. Examination in polished section shows at least seven recognizable varieties, not including three that contain nickel and cobalt. It has not been possible to separate these varieties and determine their chemical composition by analyses, and the composition assigned to them is that given in the textbooks. It is entirely possible that some of them, especially those high in copper and low in arsenic, may be solid solutions or alloys and not definite minerals. Domeykite (Cu_3As) is highest in arsenic, and it was the earliest to form, being preceded only by magnetite and the nickel-cobalt arsenides. Domeykite is veined and replaced by algodonite, whose formula has been given as Cu_6As. Etching polished surfaces of algodonite shows that it is not a simple substance but an intergrowth of two minerals, which are here designated *α* and *β* algodonite. Algodonite is in turn succeeded and in part replaced by substances still higher in copper; several of these are now recognized, though all were formerly called whitneyite and assigned the formula Cu_9As. These are here designated *α*, *β*, *γ*, and *δ* whitneyite. They may well be solid solutions or alloys rather than definite compounds. Etching tests show that these sub stances are veined by native copper. Thus there is a definite order of deposition in the series. This order is invariably domeykite, algodonite, whitneyite, and native copper. Each mineral partly replaced its immediate predecessor; domeykite, so far as observed, has not been replaced by whitneyite or native copper, nor algodonite by native copper. Each arsenide was followed by the one next higher in copper content, until finally native copper was precipitated. The order of deposition of the individual members of the general algodonite and whitneyite group can not be so definitely stated. Even this, however, seems to be consistent with the general rule of elimination of arsenic. For example, where whitneyite was replaced or followed by copper, the whitneyite is of the *γ* or *δ* variety, but the whitneyite that replaced algodonite is in most places the lighter, more arsenical *α* or *β* whitneyite. In some specimens two members of the whitneyite group seem to grade into each other, in stead of having sharply defined contacts. Every specimen of algodonite so far examined is an intimate intergrowth of the two constituents *α* and *β* algodonite. Where a predominates over *β* the color of the mixture is tin white, but with a predominance of *β* the specimen has a distinct pinkish tone, as if *β* had a higher copper content. The algodonite that has replaced domeykite generally has a predominance of the a variety, but where algodonite is replaced by whitneyite the *β* variety is predominant.

[67]Koenig, G. A., On artificial production of crystallized domeykite, algodonite argentodomeykite, and stibiodomeykite: Am. Philos. Soc. Proc., vol. 42, pp. 219- 237, 1903.

Although the physical and chemical properties as described serve in general to determine roughly the arsenides present in a given specimen, examination in polished section makes it possible to differentiate varieties that are not distinguishable in the hand specimen and to determine their paragenesis. Below is a list of the copper arsenides arranged in the order of their known or inferred copper content, together with their diagnostic properties in polished section.

Diagnostic properties of copper arsenides

Name	Composition	Color of polished surface in oblique light	Results of etching polished surface			Remarks
			HNO_3	HCl	NH_4OH	
Domeykite	Cu_3As	White	Effervescence blackens.	Color unchanged, develops Δ cleavage patterns.	Turns yellow-brown.	After rubbing on plate with fine abrasive is dull gray compared with algodonite under similar conditions.
Algodonite:						
α	Cu_6As	Creamy white	Effervescence deep purple.	Brings out faint difference between α and β.	Blackens	After etching with HNO_3, polish gently and α is smooth blue-gray; β is white.
β		Pinkish creamy white.	Effervescence dark brown.			
Whitneyite:						In general the series shows colors grading from algodonite to that of pure copper. γ is decidedly pinker than others. δ is decidedly lighter than copper. All characterized by immediate browning with HCl.
α	Cu_3As	Deep creamy white	Effervescence brown	Faint brown rubs off	Little effect	
β		Deep cream	do	Deep brown rubs off	do	
γ		Pink (like breithauptite?).	Effervescence chocolate-brown.	Deep chocolate-brown rubs off.	do	
δ		Copper-cream	Effervescence brown.	Deep brown rubs off	do	
Copper	Cu	Pink (brownish pink with γ whitneyite?).	No color change	Fine solution pits, dull but no color change.	do	The color and lack of browning by HCl used to distinguish from the whitneyite group.

The several groups of arsenides are not difficult to recognize in hand specimens. The colors range from the white of domeykite and algodonite through the pale copper-reds of the whitneyite group to the copper-red of pure copper. One per cent of arsenic in arsenical copper causes a perceptible lightening of the color. The malleability of the minerals also varies. Domeykite is decidedly brittle, algodonite is much less so, and the whitneyite group is decidedly malleable but less so than pure copper. (See pl. 70.)

Heating in glass tubes drives off the arsenic easily from domeykite and algodonite, but with extreme difficulty from whitneyite, the lower arsenic compound.

The alterations of the arsenides are characteristic. Domeykite rapidly tarnishes to a chalcopyrite-yellow. Some has weathered to cuprite. The bright-green coloration that has developed along the arsenide fissures underground since they were opened by mining is probably due to the formation of an arsenate and seems to be chiefly connected with algodonite. Whitneyite tarnishes brown rather quickly.

Origin.—It is pointed out in the section on ore deposits (p. 132) that in general, although there are some notable exceptions, the higher the lode is in the series the lower its arsenic content. This is also true of the occurrence of sulphides of copper, and what is said of the distribution of arsenic may be said of the distribution of sulphur. The explanation of this relation, which seems to be consistent with the chemical theory favored by the writers, is that the solutions which traversed the lower beds had not been in intimate contact with the oxidizing environment of the lodes for as long a time as those which deposited copper in the higher beds, and for that reason their arsenic and sulphur failed to become completely oxidized into a more soluble state. There are three possible reasons why those solutions should have had less opportunity for oxidation: (1) The rocks toward the base of the series are more fissured than those higher up, hence solutions could find in the fissures a more permeable pathway than the oxidized amygdaloids. The arsenide's and sulphides occur by far the most abundantly in fissures. (2) The occurrence of several intrusive bodies toward the base of the series may mean that a magmatic source for the copper lies much nearer the present surface in this part of the series than elsewhere. Thus the failure of complete oxidation of the solutions may be due to the fact that in that general area they were too close to the magmatic source. (3) Similarly, if the shattered zone associated with the Keweenaw fault is regarded as the main trunk channel for solutions emanating from a deep magmatic source, such solutions had not been in contact with an oxidizing environment sufficiently long when they traversed the rocks adjacent to that trunk channel.

The presence of sulphides in the Nonesuch lode near the Porcupine Mountains does not help in deciding which of these possible causes had the greatest effect, for major faulting, fissuring, and intrusive rocks are all present near by.

Another possibility which merits consideration is that the deposition of arsenides and sulphides in the fissures occurred subsequent to the main period of mineralization and was due to a change in the character of the solutions, the later ones being higher in sulphur and arsenic.

It is certain that in his investigations of these copper arsenides Koenig[68] had very complex mixtures to deal with. His mohawkite and keweenawite and other new species were undoubtedly such mixtures. Modern metallographic methods were not available at the time he did his work.

It is to be hoped that the problems of these arsenides, the solutions of which have just been started in this work, will be further studied by others. The present writers have specialized on the material found in the Michigan copper district. It will be interesting to learn what specimens from other districts reveal. It would seem that chemical analyses and metallographic work upon synthetic compounds of copper and arsenic, if cooling curves are taken and the constitution diagram of those metals is kept in mind, would throw some light on the nature of the minerals.

Cobalt and nickel minerals have been recognized in a fissure in the Seneca mine, on the third level, 2,100 feet north of No. 2 shaft. The minerals present in the other arsenide fissures crossing the Kearsarge are present in this fissure—that is, domeykite, algodonite, and whitneyite. The microscope reveals in addition at least three other arsenides, one a white mineral, another a pinkish white, and the third a brownish pink, like niccolite. Chemical tests by Mr. Hillenbrand at the Calumet & Hecla smelter show abundant nickel. Borax bead tests show cobalt. The late George Heath, of the Calumet & Hecla smelter, stated that in the arsenides of the Ahmeek fissures there is but a trace of nickel. Therefore the nickel and cobalt are probably accounted for by the new minerals. The sequence in age seems to be, first, the white mineral, next the pinkish white, then the domeykite, followed by the other copper arsenides in their usual order. The brownish-pink mineral is present in very minor amounts in the sections seen, and its relations were not determined. The magnetite was formed early in the nickel-cobalt stage.

The tests on the white and pinkish-white minerals so far have not corresponded to those of any described mineral. The pinkish-white mineral shows the following properties in polished section: Hardness, that of magnetite; effect of HNO_3, effervesces, fumes slightly brown, no coating or etching; of HCl, negative; of $HgCl_2$, brown, rubs clean; of KCN, negative; of $FeCl_3$, negative. The white mineral is hard and is negative to HNO_3, HCl, and $FeCl_3$.

If further investigation of these nickel-cobalt arsenides should establish them as new species, it would be desirable to retain the names mohawkite and keweenawite which Koenig gave to certain intimate mixtures of arsenides from these fissures.

[68]Koenig, G. A., op. cit.

HALOIDS

Fluorite (CaF_2) is reported from the Indiana mine by Hore and from Eagle River by Seaman. It was also noted in diamond-drill cores from the Onondaga exploration north of Lake Gogebic, where it occurs in fissures in quartz porphyry.

OXIDES

Quartz (SiO_2) occurs as an original mineral in the felsites and quartz porphyries. It is present in practically all lodes and fissures throughout the district as a vein filling, as a filling of vesicles, and replacing other minerals and rock. It is perhaps most abundant in the Evergreen lodes and the Isle Royale lode, but it is plentiful in others, as the Baltic and Pewabic and locally in the Osceola and Kearsarge. In the fissures it is particularly abundant with the arsenides. Quartz was formed through the greater part of the ore period but most abundantly in the middle portion. It replaced the rock minerals and some of the earlier ore minerals and was in turn replaced by some of the later minerals. Chalcedony occurs as lining of vugs in the Pewabic lode and in amygdules in the Kearsarge lode. It has replaced zoisite and calcite in many places.

Cuprite (Cu_2O) occurs in well-formed crystals at the Indiana mine as an oxidation product of copper; it occurs similarly at the Algomah mine, where it is largely altered to tenorite. The copper in many of the mine openings is colored with a film of cuprite. In places this film has clearly formed after the mines were opened. In other places, especially in the higher levels, it probably formed before the mines were opened.

Tenorite (melaconite, CuO), the black oxide of copper, is especially abundant at the Algomah mine and at Copper Harbor and doubtless occurs elsewhere. It is a product of oxidation of other minerals.

Atacamite ($Cu_2Cl(OH_3)$) occurs in well-formed radiating crystals as an oxidation product at the Algomah mine.

Hematite (Fe_2O_3) is apparently a primary mineral in the felsite and in the felsite pebbles of the conglomerates. The abundant hematite in the red tops of the lava flows is believed to have been formed from magnetite and the iron silicates or from the glassy portion of the tops of flows, or possibly in part crystallized directly during the solidification and cooling of the flows. Deeper in the flows the hematite has formed from magnetite and olivine, likewise probably during solidification. This process is fully discussed in the section on oxidation of lava tops (p. 38). Hematite occurs in small amount in some of the veins that contain sulphide and arsenide. In these it is usually associated with ankerite. In the conglomerate specular hematite is present in some of the iron-rich porphyry boulders. Specular hematite also occurs sparingly in fractures in both the conglomerate and amygdaloid lodes. It is included in the red feldspar of the lodes. Characteristically hematite has been destroyed near copper, and the iron has been either recombined or removed. The formation of hematite mainly preceded the ore-forming period. During that period a little was formed, probably by the recrystallization of earlier hematite.

Ilmenite ($FeTiO_3$) occurs as a primary mineral in traps. It has been altered in places to hematite and titanite.

Brucite (MgO_2H_2) occurs in vugs in the Isle Royale and Kearsarge lodes. It is a late mineral of the ore period. In the one specimen from the Kearsarge lode it has replaced laumontite. In the Isle Royale mine it was replaced by sericite

Magnetite (Fe_3O_4) was originally an abundant primary mineral in nearly all the flows, but it has been entirely altered to hematite in the tops of the flows and throughout some flows. This alteration is discussed in connection with oxidation of lava tops (p. 34). Magnetite is present as grains in some of the conglomerates, as the Great conglomerate and the Houghton conglomerate, but in most of them it has been altered to hematite or limonite. It is rarely present in the fissure veins. The magnetite of the flows is titaniferous, and hematite, titanite, and rutile were formed from it on alteration.

Rutile (TiO_2) occurs in basalt as an alteration product of titaniferous iron ore, and it occurs also in the felsites, where it was possibly derived from biotite.

Manganite ($Mn_2O_3.H_2O$) occurs as small crystals in vugs in the Calumet & Heel a conglomerate. At the Manganese mine, near Copper Harbor, it occurs with other manganese minerals as a “vein,” essentially coinciding with an amygdaloid a short distance below the Great conglomerate. The “vein” was opened for a few hundred feet along the strike, and some ore was shipped from the mine.

Pyrolusite (MnO_2) occurs at the Manganese mine, near Copper Harbor.

Limonite ($2Fe_2O_3.3H_2O$) occurs sparingly on weathered surfaces of trap. It is present in the conglomerates, probably as alteration product of magnetite. It is rarely seen in the amygdaloid lodes.

CARBONATES

Calcite ($CaCO_3$) is perhaps the most widespread mineral of the ore-forming period. It occurs as crystals in open cavities and replaces other minerals and is everywhere present in veins, amygdaloids, and conglomerates. It was formed from about the middle to the end of the ore-forming period, and therefore it has replaced many minerals and has itself been replaced by several. It occurs in the pegmatitic lenses in some of the thick traps. It is also being formed in the present mine workings where water is dripping in the upper levels and around masses of copper in the walls of openings in the deep levels. In many places crystals of calcite inclose small crystals of copper.

Ankerite ($(Ca,Mg,Fe,Mn)CO_3$, composition variable) is common in the sulphide and arsenide veins and is also abundant in parts of the Baltic lode as a lode mineral. In sulphide veins it commonly occurs next to the walls, with sulphides in the center. The same relation is shown in the Baltic lode, where the carbonate lines cavities and incloses sulphide. It has also replaced the lode rock. Where it is associated with calcite the calcite is later. The mineral apparently was formed at intermediate to late stages in the ore period and is closely associated with sulphides and arsenides.

Malachite ($Cu_2(OH)_2.CO_3$) was noted particularly at the Algomah mine as an oxidation product. It is doubtless present in small amount at other places.

SILICATES

The plagioclase series of feldspars, consisting of isomorphous mixtures of albite ($NaAlSi_3O_8$) and anorthite ($CaAl_2Si_2O_8$), is represented by plagioclase of intermediate composition, which forms an abundant original constituent of all the flows. Albite is present in the felsites. The feldspars of the flows underwent little alteration during the oxidation of the flow tops, the microlites of plagioclase being still remarkably fresh. Plagioclase was, however, one of the earliest minerals to be attacked by the ore solutions, though locally it remains remarkably fresh in otherwise altered rock. The feldspar was commonly replaced by chlorite, epidote, zoisite, sericite, or calcite, but prehnite or any of the later minerals have replaced plagioclase.

Albite in relatively small amount is present in many places as one of the later minerals of the ore-forming period.

Orthoclase ($KAlSi_3O_8$) occurs in three distinct ways—as an original mineral of the felsite, as an early mineral of the ore period (red feldspar), and as adularia, a late mineral of the ore period. The original orthoclase of the felsites occurs both as phenocrysts and in the groundmass. Red feldspar, probably of variable composition, is abundant in several of the lodes and is also present in many fissures. It is especially abundant in the Butler lode and adjacent lodes, in the Superior lode, and in parts of the Kearsarge and Osceola amygdaloids. It is present but not abundant in the conglomerates. It occurs in fissures and amygdules, and it replaces the rock, especially in the Evergreen and succeeding lodes but to some extent in most of the other lodes. It was one of the earliest minerals of the ore period and was replaced by chlorite, epidote, and later minerals. Copper occurs with red feldspar, but the association is not notably close. The feldspar, like many minerals of the ore period, is far more widespread than copper.

Adularia occurs to a minor extent in lodes and fissures as well-formed white to pinkish crystals, usually in open spaces. It was apparently a relatively late mineral of the ore period.

Pyroxene ($Ca(Mg,Fe)Si_2O_6$) is an abundant primary mineral of all the basic flows. Its usual alteration is to hematite and serpentine. In places it is stained with limonite. It was rather resistant to alteration by the ore solutions, but where the alteration was intense it was replaced, like the other rock minerals.

Hornblende was noted in the Greenstone flow associated with biotite.

Olivine ($(Mg,Fe)_2SiO_4$) was an early mineral to crystallize in most of the lava flows. It is now mostly altered, characteristically to serpentine or bowlingite and hematite. These minerals were in places further altered to others. Fresh olivine was observed only in the coarse phases of the Greenstone flow.

Zircon ($ZrSiO_4$) occurs as a primary mineral of the felsites.

Pumpellyite ($6CaO.3Al_2O_3.7SiO_2.4H_2O$), provision ally called zoisite, occurs in bluish-green lath-shaped crystals or needles, in most places in radiating groups. It is this mineral that gives the characteristic bluish- green color to much of the lode material in the mines in the south end of the district. It is near zoisite in composition but differs from zoisite crystallographically. Doctor Palache[69] has described this mineral in detail.

Analysis of pumpellyite

[Helen E. Vassar, analyst]

	Analysis	Molecular ratio	
SiO_2	37.18	0.616	0.616=7
Al_2O_3	23.50	.260	.293=3
Fe_2O_3	5.29	.033	
FeO	2.09	.029	.524=6
MgO	3.18	.079	
CaO	23.08	.411	
MnO	.13	.002	
Na_2O	.19	.003	
K_2O	Trace.		
H_2O+	6.28	.349	.349=4
H_2O-	.06		
	100.97		

The mineral is abundant in all the amygdaloid lodes and in all the fissures. It is present but not usually abundant in the conglomerates.

It is especially conspicuous in the Isle Royale lode and in the Evergreen and succeeding lodes, but hardly more so than in parts of the Baltic and Pewabic lodes. It occurs

in open cavities and replaces the rock. In many places pumpellyite with quartz has partly replaced large volumes of rock. It commonly followed epidote in formation but preceded copper. It replaced the earlier minerals of the ore period, such as chlorite and epidote, and in turn was replaced by the later minerals, including copper. It is not usually abundant in highly oxidized rock, such as the top of the Kearsarge amygdaloid. It is closely associate with copper in many places, but apparently, like many of the gangue minerals, is far more widespread in occurrence than copper. The lodes of the Pewabic series in particular in numerous places are rather highly pumpellyitized where they are not known to contain abundant copper.

[69]Palache, Charles, and Vassar, H. E., Some minerals of the Keweenaw copper deposits; pumpellyite, a new mineral; sericite; saponite: Am. Mineralogist, vol. 10, pp. 412-418, 1925.

Epidote (composition variable, approximately $HCa_2(Al,Fe)_3Si_3O_{13}$), a yellow-green mineral, is everywhere abundant in both veins and lodes, being perhaps especially abundant in the Evergreen and succeeding lodes of that series and in the Isle Royale lode. It is also abundant locally in the Calumet & Hecla conglomerate. Epidote characteristically has replaced the rock minerals, though it has also been formed in openings. It commonly first replaced plagioclase but eventually replaced much of the rock in mass. In the Calumet & Hecla conglomerate it replaced sandstone lenses. In the Kearsarge lode it is relatively abundant in the upper, highly oxidized portion as contrasted with the lower, less oxidized portion. The iron entering the epidote was apparently derived from the hematite of the rocks. Epidote is one of the early minerals of the ore-forming period, in the main preceding copper, but it also appears to have been formed to a slight extent later than copper as it cuts anhydrite and sericite—in the Isle Royale mine, for instance. Epidote is in many places closely associated with copper, but, like chlorite and calcite, it is far more widespread than the commercially valuable copper minerals.

Tourmaline occurs in felsite fragments in the conglomerates. It is unrelated to the copper mineralization.

Laumontite ($CaAl_2Si_4O_{12}.4H_2O$) is usually pink or salmon-colored, but in places, especially in some vugs, it is white. It occurs in practically all the fissures and amygdaloids. It is abundant in many fissures and locally in the amygdaloids but is practically absent from the conglomerates. It is one of the later minerals of the ore period and has replaced the earlier minerals but was in turn replaced by some of the later minerals. It was mainly later than copper, but a little copper was formed after the laumontite. It is not closely associated with copper and is far more widespread than copper in occurrence. Where laumontite is abundant the lodes are usually relatively poor in copper.

Natrolite ($Na_2Al_2Si3O_{10}.2H_2O$) occurs with analcite and adularia at Copper Falls.

Analcite ($NaAlSi_2O_6.H_2O$) occurs commonly as a vein mineral, more rarely in vugs in the lodes. It occurs in vugs as white, well-formed crystals, in many of which the centers are partly dissolved. In veins it rarely shows crystal form and is pinkish in color. It is one of the late minerals of the ore-forming period but in places was followed by saponite and calcite. It is a common mineral but nowhere abundant. Most occurrences were noted in the Kearsarge lode.

Stilbite ($CaAl_2Si_6O_{16}.6H_2O$) occurs in the Osceola amygdaloid and at Copper Falls.

Heulandite ($CaAl_2Si_6O_{16}.5H_2O$) is one of the rarest zeolites of the district.

Thomsonite ($CaAl_2Si_2O_8.21/2H_2O$) occurs mainly as a filling of amygdules but also in veins. It is usually not closely associated with copper.

Apophyllite was observed in the St. Clair, Robbins, Cliff, and North American fissures. It is one of the latest minerals.

Chlorastrolite occurs as amygdule filling in flows on Isle Royal. It is worn from the matrix by wave action, and the stones are gathered on the beaches.

Faujasite ($H_2(CaNa_2)Al_2(SiO_3)_5.9H_2O$) from Copper Falls is in the Whitney collection.

Datolite ($H_2Ca_2B_2Si_2O_{10}$) occurs in both fissures and lodes. It is probably present in most of the amygdaloid lodes, but it is relatively abundant in the Evergreen and succeeding lodes, especially at the Mass Mine, in parts of the Kearsarge and Osceola lodes, in parts of the Pewabic lodes, and in the Ashbed lodes in Keweenaw County. It has not been noted in the conglomerate lodes. It occurs in fissures at many places and is abundant at the Copper Falls (Owl Creek) and Petherick fissures, where locally at least it formed the main gangue mineral. Datolite forms both well-developed crystals and dense porcelanic masses. The crystalline datolite occurs in both fissures and lodes. It may be pink from included copper, and where the crystals are small they occur as a loose, crumbly granular aggregate. The porcelanic variety occurs characteristically as irregular spheroidal masses with a botryoidal surface. (See pl. 66.) These masses of datolite commonly contain many small specks of copper, which are usually concentrated near the surface of the mass, though less commonly the concentration is toward the center. This variety has been found most abundantly in the higher levels of the Pewabic lodes but is present in other lodes. Datolite apparently was one of the intermediate to later minerals of the ore period.

Prehnite ($Al_2(SiO_4)_3Ca_2H_2$) commonly occurs in radiating crystal aggregates but in the veins especially may appear massive. Much of it has a light apple-green tint, but it varies greatly in color, some of it being nearly black. It is abundant in veins throughout the district. It is present in most of the amygdaloids, where it has filled vesicles or replaced earlier minerals or rock. Locally it is abundant in the amygdaloids, as in the Osceola lode,

where it largely replaced basic sediment. It is rare in the conglomerates. Prehnite was formed mainly as an intermediate mineral of the ore period, but some was later. In the veins it is very commonly associated with copper, which in many places is disseminated through it in minute grains. The highly prehnitized amygdaloid, however, is not usually high in copper. Prehnite has been replaced by the later minerals.

Sericite (muscovite, $Al_3KH_2Si_3O_{12}$) has mainly replaced rock and earlier ore minerals but also filled open spaces. It is most abundant as a replacement mineral in the walls of the arsenide and sulphide fissures and in some of the lodes, as the Isle Royale and locally in the Baltic. In the Isle Royale lode it is rather abundant as a soft talcose mineral replacing fragmental amygdaloid. Sericite seems to have been formed from a moderately early stage in the ore-forming period to a rather late stage.

Analysis of sericite from Isle Royale amygdaloid

[Helen E. Vassar, analyst]

SiO_2	50. 27	K_2O	9. 61
Al_2O_3	27. 71	Na_2O	. 15
FeO	. 53	H_2O+	4. 68
Fe_2O_3	1. 87	H_2O-	1. 44
MnO	. 03	CO_2	. 76
CaO	1. 06	TiO_2	Trace.
MgO	2. 39		

Biotite ($Al_2Mg_2KHSi_3O_{12}$, with variable proportions of ferric and ferrous iron) is a rare primary constituent of some of the basic lava flows, such as the Ashbed group and the Greenstone flow.

Chlorite (delessite, $H_{10}(Mg,Fe)_4Al_4Si_4O_{22}$, variable) occurs abundantly as a vesicle filling and as a vein mineral, and it has also replaced rock minerals. It is particularly abundant in some of the veins and has replaced the adjacent wall rocks. In the amygdaloids it is especially conspicuous in the less oxidized parts, such as the lower portion. In the Calumet & Hecla conglomerate it has replaced some of the iron-rich pebbles, where it is associated with copper. At White Pine it surrounds hydrocarbon and has been replaced by copper. Some chlorite was probably formed during the cooling and solidification of the lavas. It was an abundant early mineral of the ore-forming period but apparently continued to form till late in that period. It replaced many minerals and was replaced by several, being very commonly replaced by copper.

Serpentine ($Mg_3H_4Si_2O_9$) is a common alteration product of olivine in the traps, and it also occurs in cavities in the amygdaloid lodes. The serpentine of the former type was earlier than the ore period; that of the latter type was formed late in the ore period.

Bowlingite is the common alteration product of olivine in many of the flows. It is resistant to alteration but has been replaced in places by prehnite and calcite.

Saponite ($Al_2O_3.MgO.10SiO_2.15$ or $16H_2O$) occurs in several of the lodes, where it has filled vesicles, replaced other minerals, and formed as a crust on other minerals. It was noted most abundantly in the Kearsarge lode. It is apparently a late mineral of the ore period.

Analyses of saponite from the Kearsarge lode

[Helen E. Vassar, analyst]

	South Kearsarge mine	Ahmeek mine
SiO_2	42. 78	42. 99
Al_2O_3	6. 44	6. 26
Fe_2O_3 / FeO	1. 27	2. 57
MgO	24. 78	22. 96
CaO	2. 35	2. 03
MnO	. 12	. 11
Na_2O	. 75	1. 04
K_2O	Trace.	Trace.
H_2O+	7. 90	6. 85
H_2O-	13. 96	13. 65
	100. 35	100. 29

Kaolin ($H_4Al_2Si_2O_9$) occurs in the Isle Royale mine on laumontite and in the Kearsarge lode as a crust on red feldspar. It is probably a late mineral of the ore-forming period. A little occurs clouding plagioclase that is believed to have been formed when the lavas were exposed at the time of extrusion.

Chrysocolla ($CuSiO_3.2H_2O$) occurs as an oxidation product at the Algomah mine and the Allouez conglomerate mine and at Copper Harbor.

Titanite ($CaTiSiO_5$) is rather abundant in all the flows as an alteration product of olivine, pyroxene, or titaniferous magnetite. In highly altered lode rock it is common as a residual mineral.

PHOSPHATES

Apatite ($Ca_5(PO_4)_3F$ or $Ca_5(PO_4)_3Cl$) occurs rather sparingly as needles or prisms in the felsite pebbles of the conglomerates and in the lava flows. It is an early original mineral of the rocks.

SULPHATES

Barite ($BaSO_4$) occurs most commonly in veins, in many places with sulphide. It also occurs in several of the amygdaloids and in the iron-rich pebbles of the Calumet & Hecla conglomerate. At the White Pine mine it is a vein mineral and a cement in the sandstone. It was among the late minerals, though followed in places by saponite, adularia, and datolite. It is widespread but nowhere abundant.

Anhydrite ($CaSO_4$) occurs in vugs and has replaced rock in the Isle Royale mine. It was also collected from the dump of the Mass mine. It seems to be of the late ore-forming stage but is veined in the Isle Royale mine by laumontite and epidote.

Gypsum ($CaSO_4.2H_2O$) occurs sparingly at numerous places, both in fissures and in the lodes. It is nowhere abundant. It appears to be a late mineral. In the Isle Royale mine it seems to have been formed from anhydrite. In the Victoria mine it has formed in puddles of salt water that stand in a crosscut.

MOLYBDATES AND TUNGSTATES

Powellite ($Ca(Mo,W)O_4$) has been reported from the Isle Royale mine, and a few well-formed crystals have been found in the Calumet & Hecla conglomerate. The

mineral is said to contain both molybdenum and tungsten.

HYDROCARBON

A dark hydrocarbon is rather plentiful in the Nonesuch lode at the White Pine mine, where it occurs in fissures and as a cement in the sandstone. In places it is surrounded by and was evidently earlier than copper. The hydrocarbon in the fissures contains abundant copper.