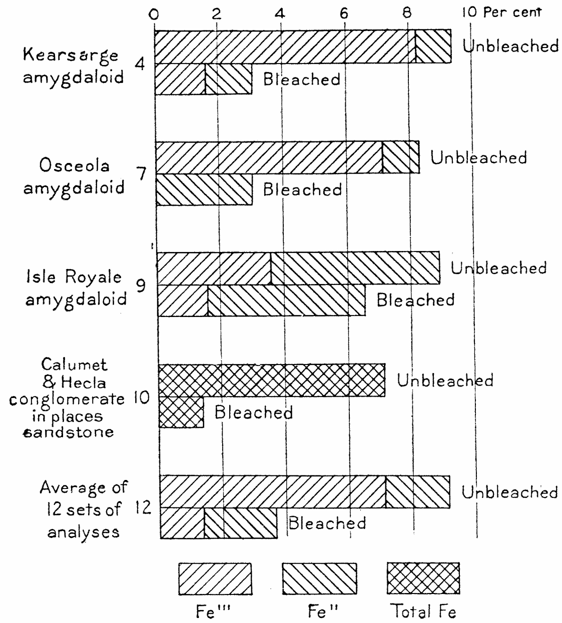

FIGURE 17.—Change in iron content of bleached rock associated with copper Numbers at left refer to table below.

Change in iron content produced by bleaching of rock associated with copper

[Specimens in collection of Calumet & Hecla Consolidated Copper Co.]

	Specimen No.	Original rock		Altered rock	
		Fe as Fe_2O_3	Fe as FeO	Fe as Fe_2O_3	Fe as FeO
1	1093	3. 42	0. 47	0. 57	0. 46
2	1489	8. 88	1. 01	. 00	2. 32
3	1593	11. 38	. 33	. 98	. 60
4	1956	8. 28	1. 11	1. 65	1. 50
5	1086	10. 30	. 85	. 15	1. 53
6	2141	8. 84	3. 31	A 5. 54	1. 46
				B 2. 65	2. 22
				C 1. 26	3. 18
7	1497	7. 15	1. 23	. 00	3. 08
8	1507	3. 56	4. 69	1. 74	4. 03
9	2165	3. 66	5. 30	1. 66	4. 92
10	1552	7. 14	--------	1. 47	--------
11	1591	9. 03	--------	1. 61	--------
12	--------	7. 16	2. 03	1. 46	2. 30

1. Pebble from Allouez conglomerate, Allouez mine, T. M. Broderick, analyst.
2. Iron-rich pebble, Calumet & Hecla conglomerate, T. M. Broderick, analyst.
3. Amygdaloidal boulder in Calumet & Hecla conglomerate, G. L. Heath, analyst.
4. Top of Kearsarge lode, Ahmeek mine, G. L. Heath, analyst.
5. Top of Kearsarge lode, South Kearsarge mine, G. L. Heath, analyst.
6. Kearsarge lode, Ahmeek mine, A, B, C, progressive stages of bleaching, G. L. Heath, analyst.
7. Osceola lode, Centennial mine, G. L. Heath, analyst.
8. Isle Royale, Isle Royale mine, H. C. Kenny, analyst.
9. Composite sample of Isle Royale lode and bleached equivalent, G. L. Heath, analyst.
10. Sandstone from lens partly mineralized, Calumet & Hecla conglomerate, H. C. Kenny, analyst.
11. Iron-rich boulder, Calumet & Hecla conglomerate, H. C. Kenny, analyst.
12. Average of 10 specimens representing lodes of different types.

Figure 17 illustrates the change in iron accompanying mineralization for a number of typical examples. The principal constituents of the unaltered and bleached rock are shown in the following analyses:

The general tendency in the alteration that produces bleaching is a removal of considerable ferric iron and a somewhat less marked conversion of ferric to ferrous iron. The fact that there has been some reduction of ferric to ferrous iron points to the probability that the iron that has been removed was also first reduced to the ferrous state, because under the conditions that probably existed ferrous compounds are more soluble than ferric.

If ferric iron was reduced to ferrous iron, there must have been an oxidation of the agent that accomplished the reduction, and it is of interest to know what that agent was.

Analyses of unaltered and bleached rock

[Specimens in collection of Calumet & Hecla Consolidated Copper Co. H. C Kenny, analyst]

	1a	1b	2a	2b	3a	3b
SiO_2	57. 7	62. 8	63. 1	53. 1	51. 4	55. 3
Al_2O_3	14. 2	16. 6	14. 7	12. 7	20. 0	21. 0
Fe_2O_3	11. 2	2. 1	10. 2 (Fe_2O_3 + FeO)	2. 1	12. 9	2. 3
FeO	1. 1	. 5				
CaO	6. 7	7. 5	5. 2	6. 4	3. 4	4. 8
MgO	3. 5	4. 2	1. 7	3. 3	2. 8	3. 8
H_2O	. 7 (H_2O + CO_2)	1. 0	. 6	1. 6	5. 0	7. 2
CO_2		. 6	1. 4	2. 2	. 1	. 5
Cu (native)	. 06	. 05	1. 55	[a] 9.75	. 48	. 38
	92. 5	95. 4	-------	------	------	------

[a] 15.0 per cent of copper removed before analysis.
1a, Dark, hard, oxidized rock from Kearsarge lode, Ahmeek mine; 1b, bleached equivalent associated with copper.
2a, Red sandstone, Calumet & Hecla conglomerate; 2b, mineralized portion of same stratum.
3a, Iron-rich boulder, Calumet & Hecla conglomerate; 3b, bleached equivalent associated with copper.

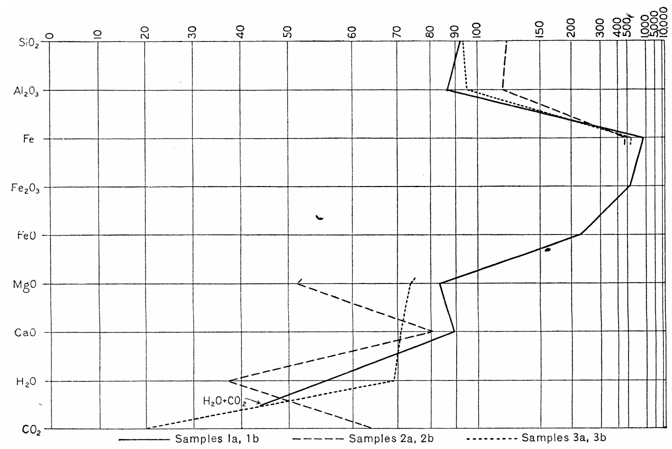

FIGURE 18.—Composition of bleached and unbleached rock. (For explanation of manner of constructing the diagram see fig. 5, p. 40.)

Among the reducing agents that might have been present are carbon, carbon monoxide, hydrocarbon, hydrogen, and sulphur or some incompletely oxidized form of sulphur. As calcite is plentiful, it is possible that some less oxidized carbon-bearing material acted as the reducing agent and was itself oxidized to the carbonate condition. Lane has, indeed, suggested that the hydrocarbon which R. T. Chamberlin found in rocks of this district acted as a reducing agent, though Lane assumes that it acted on oxidized copper compounds. Hydrocarbons are, however, no more plentiful in the rocks here than in many other regions where no such peculiar results as deposition of native copper and destruction of hematite are found; there is no significant connection between the occurrence of calcite and either deposition of native copper or bleaching, and a the White Pine mine, where a solid hydrocarbon, most probably derived from the adjacent carbonaceous shale is present in fair abundance, the amount of bleaching is not conspicuously greater than where hydrocarbon occurs only in mere traces or not at all, but sulphides are more plentiful there in proportion to copper than at any other place in red rocks in the district.

It has been suggested that the bleaching around copper resulted from the reaction between the ferric oxide and the metallic copper and therefore occurred after the copper was deposited. Such a reduction of ferric oxide is readily accomplished and is, indeed, a difficulty in chemical analyses when ferric oxide is determined in the presence of metallic copper. Moreover, some of the copper ore when brought to the surface shows a thin film of green copper carbonate or of red oxide of copper surrounding the metal, and this has been suggested as the oxidized copper compound produced in the reaction cited. Examination and inquiry show, however, that the copper when the rock is first broken is not green but bright and metallic or at most covered by a mere film of cuprite. Moreover, the removal of hematite is not the only effect in the bleached areas. In the amygdaloid lodes in particular, the destruction of hematite was accompanied by an intense miner alogic, chemical, and textural breakdown of the rock surrounding the copper—an alteration that would not be likely to result from the mere action of the metallic copper on the rock.

There is no doubt that the metallic copper was replacing the bleached rock—that is, that the removal of iron, although everywhere going on at the same time- as the deposition of copper near by, was accomplished at any given point in advance of the precipitation of copper; bleaching was the front of the alteration wave; replacement by copper was the end.

The practical absence of bleached spots without accompanying copper further indicates that deposition of copper and bleaching of rock were intimately associated and that copper has not been removed since its deposition. The exceedingly low copper and iron content of the mine waters likewise proves that reaction between iron and copper is not now in progress, or, if at all, to only a very slight extent.

The hypothesis that copper sulphide solutions acted as the reducing agent that destroyed the hematite appears to fit the facts in a satisfactory way and at once explains both the bleaching of the rock and the deposition of copper in the native state. The power of the metallic sulphides as reducing agents is shown by the ease with which they take up oxygen to form sulphates—far more readily, for instance, than the ferrous iron minerals succumb to oxidation. In the oxidation of the "sulphide solution" the process has gone so far as to oxidize the sulphur, but the copper was deposited as metal.

The copper occurs generally in irregular masses rather than uniformly distributed through the lode. It is impossible to assume that the replaced rock itself could supply enough reactive agent of any kind to cause the precipitation of three times its own weight of copper, either in the small particles or in the great masses tons and even hundreds of tons in weight. It is more likely, as suggested in connection with the saturation hypothesis (p. 129), that the reaction was taking place as the solution passed through the lode until such a degree of concentration was reached that copper precipitation had to begin.

In places copper is accompanied by only slight if any immediately local bleaching. This is the case, for example, in parts of the Pewabic lode, in the upper levels of the Calumet & Hecla conglomerate mine, and in the copper-bearing fissures that cut the Kearsarge lode.

Wells has found in his experiments that the metallic copper commonly does not replace the solid reagent that causes the precipitation but rather grows out into the free solution, often not in contact at all with the precipitant. The laboratory experiments thus appear to be in harmony with the natural occurrence.

Copper was deposited in the cross fissures chiefly at and near their intersections with thick hematite-rich lodes. Where in the Ahmeek and Mohawk mines some of these fissures, notably the Mass fissure, cross the Kearsarge lode, the destruction of hematite is of a different type from that seen in the bleached rock that so commonly surrounds the copper. Along these copper-bearing cross fissures for a width of 10 to several tens of feet the Kearsarge lode is darker and leaner than usual. Along the Mass fissure in the Ahmeek mine the dark lean zone extends for 80 to 100 feet on each side of the fissure. Determination of iron oxides shows the following contrast between the dark material and the normal red material near by:

Alteration of Kearsarge lode near Mass fissure

	Fe as Fe_2O_3	Fe as FeO
Normal red lode	8. 11	0. 68
Altered dark lode	7. 49	6. 45

The changes indicated by these analyses suggest that the solutions moving generally along the fissure but soaking into the Kearsarge lode were at that time and place able to destroy but little of the ferric iron but were, on the contrary, relatively highly charged with ferrous iron, which they precipitated. Microscopic examination of the dark material reveals a difference in two respects from the normal rock of the Kearsarge lode—(*a*) much chlorite has been introduced throughout and accounts for about all the added ferrous iron; (*b*) all the finer flakes and particles of hematite have been removed and with them the red color, but the larger grains of hematite, which make up the greatest part, by weight, are still present and account for the small decline in ferric iron content notwithstanding the marked change in color.

It seems probable that the solutions moved along the intersection of the fissure with the Kearsarge lode; the main avenue of flow was through the fissure, but there was always local penetration into the permeable lode, and in consequence the solutions, before reaching the levels now exposed in the mine, were oxidized at the expense of the hematite of the lode and became charged with ferrous iron and uncombined copper. Having undergone these reactions, the solutions deposited the constituents with which they had become saturated, but the copper was deposited mainly in the fissure itself as masses of native metal while the ferrous iron, which could not be precipitated alone, was deposited as chlorite partly along the fissure and partly in the lode. The lode rock, because of its glassy condition, was probably more susceptible to reaction than the trap that in the main bounds the fissure.

The channel afforded by the fissure and the immediately adjacent parts of the lode probably constituted an easier avenue for ascent than that offered by the lode alone. The solutions flowing along the fissure, therefore, should have reached the altitude of the present mine workings before those which moved up the lode and accomplished the normal mineralization characteristic of the Kearsarge. If so, the alterations just described had been accomplished, in part at least, near the fissure by the time the normal lode solutions reached that point. With the most finely divided and hence the most reactive of the hematite already gone, the lode near the fissure was less favorable for precipitating copper from the later solutions than the lode away from the fissure.

It is not definitely known whether such copper as occurs in the darkened zone along the fissure was deposited by the fissure solutions, by the lode solutions, or by both. The descriptions of certain of the fissure veins of Keweenaw County mined in earlier days, notably the Cliff and the Central, indicate that some lodes contained sufficient copper to warrant exploration of them outside the limits of the fissures or fissure zone; and as a rule the exploration of these "floors," as they were called, was abandoned not far from the fissures. The natural inference is that certain of the lodes close to the cross fissures had been mineralized by the solutions, which in the main were traveling along the fissures themselves.

The arsenide fissures that cross the Kearsarge lode carry iron carbonate in considerable abundance, and an iron carbonate is characteristically present in the sulphide fissures in and near the Baltic lode. It is evident, therefore, that the solutions that traversed the fissures were also relatively rich in ferrous iron.

PRESENCE OF SULPHATES

If copper sulphides were oxidized and in consequence precipitated native copper, the oxidation would obviously affect the sulphur. What condition or combination of sulphur might actually be expected?

Elemental sulphur is known to be formed from the oxidation of sulphide and from the oxidation of certain sulphur-bearing hot-spring waters, but these occurrences do not justify the inference that sulphur should have been formed in the Michigan copper deposits. Sulphur dioxide, which is present in volcanic emanations, may be produced in part by the oxidation of sulphides, directly or indirectly, and it is known to be formed in small quantity from the artificial oxidation of pyrite under certain conditions. The sulphite salts derived from it (or from sulphurous acid—$H_2O + SO_2$) are either easily soluble or unstable, and so it could not be expected that any of these sulphur compounds would now be present, no matter how much SO_2 may have formed.

In nature oxidized sulphur occurs by far the most commonly as sulphate, and when solid sulphides oxidize, sulphates and sulphuric acid are formed from all or nearly all the sulphur of the sulphides; moreover, as has been indicated elsewhere,[37] the sulphates present as gangue minerals in primary ore deposits have probably been derived by hypogene oxidation of sulphur-bearing solutions. Sulphates are the only oxidized compounds of sulphur that are likely to form minerals and be found in the deposits, but, as only a few of the sulphates are notably insoluble, it is not to be expected that even the sulphates will be found in abundance.

Sulphuric acid, if formed, would undoubtedly unite with one or more bases; so only sulphate salts would be expected. If copper sulphide were oxidized by hematite, one probable product of the reaction would be ferrous sulphate. It is certain, however, that if the solutions contained bases that form relatively insoluble sulphates such sulphates would form and be precipitated in accordance with their abundance and solubility. The sulphates of most of the common elements in the Michigan rocks are highly soluble. This is true of sodium, potassium, magnesium, and aluminum, and it is true of ferrous iron except when in contact with an oxidizing agent of stronger power than hematite. The present mine waters contain only slight and occasional traces of sulphates, though gypsum is being precipitated from mine waters in the Victoria mine; but unless it is shown that the present mine waters are part of those that deposited the ores, the presence or absence of sulphates in these waters is of no particular significance.

The barium and calcium sulphates barite, anhydrite, and gypsum occur in the Michigan deposits and are the only sulphates sufficiently insoluble to be expected. Barite accounts for all of the barium, so far as known, but the two calcium sulphates account for only a very small fraction of the total calcium present in the lodes. The total quantity of sulphate represented by these three minerals is far too little to account for all the sulphur of the solutions if the native copper came from sulphide. In explanation of this discrepancy, reference may be made to the behavior of the sulphate radicle in regions where sulphide ores undergo superficial oxidation. In camps like Bisbee and Globe, in Arizona, great quantities of sulphide ore contained in limestone have been oxidized near the surface, with the production of correspondingly great quantities of soluble sulphates and sulphuric acid; these have plainly enough reacted with the adjacent limestone and must have formed calcium sulphate on an enormous scale, yet the mineral gypsum is present only sparsely in and near these oxidized ore bodies. This is due in part to the rather ready solubility of calcium sulphate in water.

[37]Butler, B. S., Primary (hypogene) sulphate minerals in ore deposits: Econ. Geology, vol. 14, p. 581, 1919.

A comparison with other districts where sulphate solutions are known to have formed in large quantity is doubtless the most reliable source of an explanation of the conditions in the Michigan district. Sufficient facts and experimental data are not available to afford a reliable interpretation of conditions so complex as those that affected the ore solutions in this district, though certain experimental facts may be pointed out. These are taken mainly from a paper by Stieglitz.[38] In a saturated water solution of calcium carbonate and calcium sulphate, at 18° C, the concentration of sulphate ions is five thousand times greater than that of carbonate ions. CO_2 increases the solubility of calcium carbonate in solution as bicarbonate, and this effect continues with increase in pressure of CO_2. The presence of other sulphates decreases the solubility of calcium sulphates. The solubility of calcium sulphate and calcium carbonate is increased by the presence of sodium chloride up to a certain concentration, above which that of both decreases. Increase in temperature reduces the solubility of calcium sulphate, which is but slightly soluble at 200° C.[39] Increase in temperature also reduces the solubility of CO_2 and in consequence probably that of calcium carbonate.

Too little is known of the influence of these several factors to warrant any definite conclusions, but perhaps the relatively high temperature of formation accounts for the fact that any calcium sulphate was precipitated. The argument with respect to oxidation products of sulphides may be summarized as follows. Such oxidation products were probably carried away for the most part in the form of gas or of soluble salt, either of which would be dissipated with relative ease soon after the mineralizing process had ceased. The only sulphates produced by sulphide oxidation that could be expected to remain are the sulphates of barium and calcium. Barite in fact is present perhaps as plentifully as the general scarcity of the element barium would permit, and anhydrite and gypsum are present as plentifully as the solubility of calcium sulphate would permit and as plentifully as they are found in other regions where calcium sulphate must have been produced in great quantity. All three sulphate minerals have been found only in the immediate vicinity of copper—a fact which may well be regarded as evidence that they are products of the reaction by which the metallic copper was formed.

The gypsum which is abundantly present, together with some barite and celestite, in and near the Coro Coro deposits of Bolivia was likewise explained by Steinmann as formed from the sulphate radicle produced by the oxidation of the sulphur of the copper sulphide solutions. Carbonates are not abundantly associated with the Coro Coro deposits.

[38]Stieglitz, Julius, The relations of equilibrium between carbon dioxide of the atmosphere and the calcium sulphate, calcium carbonate, and calcium bicarbonate of water solution in contact with it: Carnegie Inst. Washington Pub. 107, 1909.

[39]Melcher, A. F., Am. Chem. Soc. Jour., vol. 32, pp. 50-66, 1910.

CHEMISTRY OF THE DEPOSITION OF NATIVE COPPER FROM ASCENDING SOLUTIONS

By R. C. Wells

As a very considerable weight of evidence indicates that the native copper in the Lake Superior district was deposited from solutions that may be characterized in a broad way as ascending, the chemical problem of accounting for the deposition of the copper as native metal is thereby delimited to a certain extent. Many of the conditions attendant on its deposition are unknown, as the solvents with all their more soluble dissolved matter have presumably disappeared, and the solids remaining are relatively few in number and simple in chemical character. But, on the other hand, the idea of ascending solutions, especially on the large scale exemplified in the Michigan district, implies certain general conditions, partly physical, partly chemical, which suggest a simple classification of the possibilities. The conditions, or rather the changes in conditions, that would naturally be expected to exist in association with ascending solutions, are, in the order of their probable importance, cooling, relief of pressure, oxidation, dilution, and reduction of acidity. Chemical suggestions based on old or new experimental evidence are offered herewith under each of these heads. The details of most of the new experiments are given in a separate publication,[40] and what is presented here is largely a summary unencumbered with the chemical details. Needless to say, the experimental field is still far from covered, as neither melts, vapors, alkaline solutions, nor solutions above 300° C. have been studied to any great extent. The results are such as could be obtained with workable solutions and the apparatus available. They are sufficient, however, both to supplement and to modify previous knowledge.

DEPOSITION BY COOLING

Hot solutions carrying cuprous sulphate deposit metallic copper on cooling. This action is believed to occur as the result of the change

$$Cu_2SO_4 = Cu + CuSO_4$$

so that only part of the copper can be thus removed from solution. Cuprous sulphate may be formed in a number of ways—for instance, by the action of copper on cupric sulphate, by the action of various sulphides on cupric sulphate, or by partial oxidation of copper sulphides.

[40]Wells, R. C., Chemistry of the deposition of native copper from ascending solutions: U. S. Geol. Survey Bull. 778, 1925.

As metallic silver accompanies copper in a few deposits it is of interest to note that metallic silver is likewise deposited when certain solutions are cooled, as indicated by the two following reactions:

$$Ag_2SO_4 + Cu_2SO_4 = 2Ag + 2CuSO_4$$
$$Ag2SO_4 + 2FeSO_4 = 2\ Ag + Fe_2(SO_4)_3$$

Gold behaves similarly, as shown by Stokes:

$$AuCl_3 + 3CuCl = Au + 3CuCl_2$$

All these equations represent reversible reactions that proceed toward the right with falling temperature and in the opposite direction with rising temperature. Vapors and melts would become more or less fixed by cooling also, but they can not be adequately discussed at present. Nor is it purposed to discuss in this place whether the theory here set forth or any of the other theories proposed would apply to a relatively local movement of the fluids from the interior of a lava flow to its cool top as well as to movement on a much larger scale.

DEPOSITION BY RELIEF OF PRESSURE

The solubility of most salts changes very slightly with pressure. For example, that of copper sulphate is known to increase with pressure some 3.2 per cent for 60 atmospheres, but that such a change could be significant in the problem under discussion seems doubtful. The solubility of gases, on the other hand, is affected to an enormous extent by changes in pressure, and, as gases like CO_2 and H_2S increase the solubility of the carbonates and sulphides to a marked extent, it is evident that relief of pressure would favor the deposition of such compounds—that is, if the gases escape from solution. Carbonates are present in the copper lodes—in fact, copper and calcite are beautifully intergrown in some specimens. The escape of carbon dioxide through relief of pressure is a possible explanation for the formation of the calcite. Nothing is known as to the solution or precipitation of copper itself through changes in pressure, except that indirectly the reducing action of hydrogen and sulphur dioxide on copper compounds is increased by moderate increases in pressure, as much more of these gases is thereby held in solution. This fact would not account for precipitation through relief of pressure, however, and it probably has no application to the problem of the deposition of copper.

DEPOSITION BY FRACTIONAL OXIDATION OF COPPER SULPHIDE

The theory that native copper was formed by the oxidation of copper sulphide in solution by ferric oxide in the rocks of the lodes has been advocated with confidence by the authors of this report, largely on the basis of field evidence. The formation of metallic copper by oxidation of the sulphide is a familiar operation in smelting practice. Analogous reactions, based on the oxidizing action of cupric salts and ferric salts, are cited in the literature. The action of acidified ferric salts on the sulphides of copper under ordinary conditions appears to result in the formation of ferrous and cupric salts, so that the problem resolves itself in part into a study of the oxidation of copper sulphide by cupric salts.

Considerable study has been given to these various possibilities. The theory here proposed implies chemical reaction. There are other grounds in the field relations for thinking that the solutions were ascending, and such solutions would be logical sources of copper sulphide. In the experimental work, however, it has not yet been possible to produce metallic copper merely by chemical reaction unaccompanied by cooling. In so far as cooling has been an essential part of the verification of the theory, the idea of ascending solutions receives support. The experimental evidence indicates, however, that at a still higher temperature than could be conveniently attained with the apparatus available, copper might be deposited by reaction alone and thus the theory rendered independent of the feature of cooling.

The steps by which ferric oxide may act on a solution of copper sulphide are as follows: Hot acid solutions containing copper and sulphur, assumed for the sake of simplicity to be equivalent in their chemical potentialities to acid solutions carrying cuprous sulphide, meet ferric oxide. The acid is decreased by solution of some ferric oxide. The ferric salt thus formed exerts an oxidizing influence, which is, however, at once balanced by the reducing action of cuprous sulphide, with the production of ferrous sulphate and cupric sulphate, as indicated by the following reaction:

$$Cu_2S + 5Fe_2O_3 + 11H_2SO_4 = 10FeSO_4 + 2CuSO_4 + 11H_2O$$

The oxidizing action of the ferric salt seems to carry the copper to the cupric stage at first and rather rapidly. Further work is needed to see if the reaction can be sufficiently slowed down through the use of less acid to yield chiefly cuprous sulphate. However, experiment shows that when further cuprous sulphide is available, its presence, as well as the decrease of acidity and the formation of water and cupric sulphate, favors the reactions

$$Cu_2S + 8CuSO_4 + 4H_2O = 5Cu_2SO_4 + 4H_2SO_4$$
$$Cu_2S + 3CuSO_4 + 4H_2O = 5Cu + 4H_2SO_4$$

The second of this pair of reactions may possibly occur at a very high temperature but has not yet been realized experimentally. However, the first reaction yields cuprous sulphate, which deposits copper on cooling. The consumption of cuprous sulphide in these ways would obviously leave less of it to be deposited as the solutions cooled, whereas copper would still be deposited on cooling. Conditions favoring the deposition of copper would be an initial high temperature; the reduction of acidity to the point where no more ferric oxide would be attacked or the local exhaustion of the ferric oxide by the solution and reduction as outlined; and, lastly, cooling and dilution of the initially heated solutions. In this way the sulphur would make its exit as ferrous sulphate. A reaction that embraces all the steps mentioned would be

$$Cu_2S + 3Fe_2O_3 + 5H_2SO_4 = 2Cu + 6FeSO_4 + 5H_2O$$

Metallic copper has been obtained experimentally from the substances indicated in this equation after heating them with water in sealed tubes to 300° and cooling.

It would be highly desirable to show that solutions of less acidity, such as those containing carbon dioxide under high pressure, would yield similar results, but the writer has not yet been able to do so. Some acid seems necessary to give the ferric iron sufficient activity to initiate the action, and the proper range appears to be one in which some ferric oxide dissolves to give a definite oxidizing action, likewise insuring that a large excess of ferrous salt will not precipitate copper, so that only the sulphur and neither the ferrous iron nor the copper shall be oxidized. Experiments at ordinary temperatures, at which the activities of the several reagents could be better regulated, would also be desirable, but the reactions involved occur too slowly at such temperatures for observation within the time available.

In view of the difficulties of reproducing the natural conditions exactly the writer feels that the experimental evidence makes this theory of the origin of the Lake Superior copper a tenable one aside from the strong field evidence in its favor.

DEPOSITION BY DILUTION

Solutions carrying considerable cuprous chloride, which is largely soluble in certain brines and other concentrated solutions, deposit copper on being gradually diluted. This mode of origin may account for some of the “mass” copper in the Lake Superior mines where cross fissures have permitted the intermingling of the concentrated brines with more dilute solutions, although it is evident that such a view renders the deposition of the mass copper not necessarily contemporaneous with the deposition in the main lodes. The reaction for this change is

$$2Na_2CuCl_3 = 4Na^+ + Cu + Cu^{++} + 6Cl^-$$

That is, a complex or double salt that exists in the concentrated solutions breaks up into single salts on dilution, with accompanying precipitation of some of the copper.

DEPOSITION BY REDUCTION OF ACIDITY

Moderate changes in acidity or alkalinity are generally characterized by the chemist as changes in the Sorensen number or pH value, which defines the hydrogen-ion concentration of the solution by the equation

$$pH = -\log[H^+]$$

in which $[H^+]$ represents the concentration of the hydrogen ion in gram-equivalents per liter.

The pH number of ore-forming solutions is of considerable importance and has not been studied as much as it deserves to be. It is obvious that as solutions pass from an acid to an alkaline reaction the solubility products of the oxides will be reached—for example, those of ferric oxide, copper oxide, and ferrous oxide—in the order of respective increasing solubility. The pH number likewise determines to a large extent the solubility of other ore and gangue minerals, such as the sulphides and carbonates. But the concentrations of the valuable metals in aqueous solutions that would be furnished by such compounds under ordinary conditions are extremely small—so small, in fact, that they are not within the range of ordinary analytical determination. It seems highly improbable, likewise, that such small concentrations have played any part in the transportation of ores; for if they had, ore deposits could not be formed at all. It is the task of the chemist who is seeking to explain the genesis of ores to point out special instances of solubility and the conditions that effect changes of solubility and to search for such conditions if they are not known.

In this investigation alkaline solutions with pH values much greater than 5.5 seemed to offer little aid toward solving the problem, inasmuch as ferrous salts, which were almost certainly present in abundance in the ore-forming solutions, would cause deposition of both copper and ferric oxide. In experiments with solutions saturated with ferric oxide at ordinary temperature, the writer has found that the pH number must be as low as 5.5 before a test for ferric iron can be obtained with potassium sulpho-cyanate. Solutions of even so low an acidity as this would therefore have geologic significance.

Precipitation of copper by ferrous salts, the agency long held to account for the formation of native copper in the Lake Superior district, can occur only if hydrolysis of the ferric salts to insoluble ferric oxide is brought about through continuous neutralization or continuously increasing heat—that is, by an increase of the pH number.

The writer’s recent experiments on this method of deposition show that when ferrous hydroxide is used as the reducing and neutralizing agent, acting on cuprous chloride solutions, both of the following reactions occur:

$$3FeO + 2CuCl = 2Cu + Fe_2O_3 + FeCl_2$$
$$4FeO + 2CuCl = 2Cu + Fe_3O_4 + FeCl_2$$

Deposition of copper from cuprous chloride solutions may be brought about even by ferrous chloride, however, when the pH number is carefully regulated—as, for instance, by means of definite proportions of acetic acid and sodium acetate. When ferrous chloride and cuprous chloride are introduced into such solutions, boiling in an atmosphere of nitrogen, no copper is precipitated if the pH value is initially less than about 5.0. In one experiment with a pH value of 5.2 a slight film, probably containing some copper, formed on the walls of the flask in the course of two hours’ boiling. With a pH value of 5.38 the deposit showed some small particles of ferric oxide, each surrounding a nucleus of minute crystals of copper visible with a lens.

Repetition of the experiment with more ferrous chloride and less cuprous chloride, in a flask with a slight film remaining from the previous experiment, gave a deposit showing under a lens or a microscope numerous crystals of copper, some spicules, and some thick crystals showing triangular faces, most of them largely covered with iron oxide, which also adhered to the glass in the form of minute lumps and floes without definite form. This iron oxide was not magnetic. The reaction occurring in this case may be written

$$2FeCl_2 + 2CuCl + 6NaCOOCH_3 + 3H_2O = 2Cu + Fe_2O_3 + 6HCOOCH_3 + 6NaCl$$

These experiments show that the use of ferrous hydroxide is not absolutely necessary for the deposition of metallic copper but that more soluble ferrous compounds suffice; that copper is a recognizable product when the reaction is made to occur very slowly; and that the deposition of copper is not dependent on cooling, a point previously unsettled.

This mode of forming native copper can obviously not be left out of consideration entirely, because of the common association of ferrous and copper compounds, and it might be viewed as an adjunct to any theory in which mixtures of ferrous and cuprous salts are involved. On it Smyth based his theory of the deposition of copper from ascending solutions, which the writer has ventured to supplement with the process of neutralization. Neutralization is suggested in order that the initial solutions can be assumed to have been not very alkaline, so that appreciable concentrations of copper salts and ferrous salts could be present in them. If the initial solutions were alkaline in the presence of ferrous compounds it is difficult to see how significant quantities of copper could have been transported. But cooling must also usually occur in ascending solutions, and, as has been shown above, cooling alone will deposit copper from slightly acid solutions containing cuprous and ferrous sulphates, so that reduction by ferrous compounds is not absolutely needed as an explanation of the deposition of the copper.

The theory of reduction by ferrous compounds has been advocated by several geologists without regard to whether the cupriferous solutions were ascending or descending, and some study has been given to the neutralizing action of the lode minerals. For example, Lane and Fernekes found that prehnite and datolite were more active than labradorite and laumontite. Lane's equation for this action is

$$2FeCl_2 + 2CuCl + 3CaSiO_3 = 2Cu + Fe_2O_3 + 3SiO_2 + 3CaCl_2$$

This equation is also an attempt to explain the calcium chloride waters now found in the deeper levels of the mines. Beyond calling attention to the small quantity of such waters in the mines, relative to the copper, the writer will only refer to the discussion of this feature of the problem in another section. All the reactions elucidated by Biddle, Stokes, Fernekes, and Lane, however, involve deposition of Fe_2O_3, whereas the present study has been devoted largely to the attempt to explain the dissolving of Fe_2O_3 in connection with the deposition of copper, which field evidence so strongly indicates.

In the light of present knowledge it appears difficult to decide whether ascending solutions would in general tend to become more acid or less acid in their reaction. In so far as they undergo oxidation they would probably become more acid, but the loss of such gases as H_2S, CO_2, and SO_2 would have the opposite effect, so that it is difficult to be certain of the final result. A number of compounds, especially those of a saltlike character, are decomposed by heat into free acids and bases, and such decomposition would certainly tend to occur to a greater or less extent at depth if such compounds are present. The acids, being volatile, could move into cooler regions, where they would recombine with any bases available, but the bases would be left at the point of decomposition. A somewhat similar result might be brought about through the action of silica as an "acid" in displacing the more volatile acids from their salts at high temperatures, but at low temperatures in aqueous solutions silica is an extremely weak acid in comparison with the strength of the bases with which it is generally associated. In other words, there seem to be several reasons for supposing that hot solutions and gases at depth would tend to be acid, whereas in cooler regions, except for the oxidation of sulphur compounds, alkalinity would become more pronounced.

This line of speculation favors the theory that copper might be deposited from ascending acid solutions through the agency of neutralization, but, if so, ferric oxide should accompany the copper, which does not generally appear to be the case in the Lake Superior ores. Moreover, this theory leaves sulphur compounds and the oxidizing action of ferric oxide out of consideration, and for that reason it can not be given first place as an explanation of the formation of the Lake Superior copper.

CONCLUSIONS

To recapitulate, five agencies that might effect the deposition of copper from ascending solutions have been considered—(1) cooling, (2) relief of pressure, (3) oxidation, (4) dilution, (5) reduction of acidity. Three of these agencies require specific constituents in the solution—the first, cuprous sulphate; the third, potential cuprous sulphide; the fourth, cuprous chloride. The third also demands an oxidizing environment for the incoming solutions, and the fifth is based on an environment that will neutralize acidity. Two of the agencies, however, may probably be excluded from consideration at once on account of the difficulty of defining the conditions with the necessary degree of certainty. These are the second and fifth.

The only application of the second agency that appears of importance as a possible cause of the deposition of native copper is the escape of certain acid gases, particularly carbon dioxide, which would leave the solutions more alkaline. This would tend to assist the deposition of copper by ferrous compounds, but other factors, such as oxidation, might tend to make the solutions more acid. It is extremely difficult to feel sure of the direction of the variation of acidity, so that it seems best to dismiss the fifth agency and with it the second from consideration. Another reason for doing so is the field evidence that the precipitating solutions seem to have dissolved ferric oxide rather than to have deposited it as required by the fifth agency for the deposition of native copper, and still a third reason is that sulphur compounds are not considered or their general absence explained by either the second or the fifth agencies.

The first and fourth agencies are so general that they might apply almost anywhere. They also require the presence of specific compounds, cuprous sulphate and cuprous chloride, respectively, and to call on them as explanations of a rather unusual type of ore, that of native copper, obviously requires some additional feature, such as, possibly, the large scale of the field. But this is as unwarranted as it is unnecessary. Thus the third agency is left as the only alternative explanation.

The third agency of deposition seems to fit the Lake Superior district best because the specific influence of ferric oxide in the gangue rocks is taken into account in determining the character of the copper mineral deposited, and it is probably unnecessary to delimit the character of the solutions further than to say that they were a potential source of cuprous sulphide and, so far as the necessities of the chemical experiments suggest, somewhat acid. The last statement might possibly imply nothing further than solutions containing large quantities of carbon dioxide. The general absence of sulphides is explained by the oxidizing action of ferric oxide, and the deposition of copper is explained by cooling of the resulting solutions at least, if not by a direct chemical reaction, which appears probable at moderately high temperatures.

SUMMARY OF GENESIS

In the preceding pages the several views regarding the origin of the native copper deposits of Michigan that have been advanced by previous investigators have been outlined, and the views held by the present writers have been elaborated in detail. A brief general summary of the argument may help the reader to judge the relative merits of all these proposed explanations. It will be emphasized in this review that the theory arrived at by the writers differs outstandingly from those of some others in postulating that the copper was deposited from ascending rather than descending solutions and was precipitated by oxidation of the ore solutions rather than by reduction. As in the fuller statement, origin, transportation, and deposition will be considered in turn.

SOURCE OF COPPER

If the deposits were formed by descending solutions the copper must have been derived from the general mass of the Keweenawan lavas, which are known to contain small amounts of copper—amounts comparable to those contained in similar rocks at many places. So far as known, this copper is pretty uniformly distributed. It is regarded by those who favor the view of descending waters as an ample source for the copper deposits. Those who favor the view of ascending solutions must also recognize this minutely disseminated copper as quantitatively sufficient, but they see no evidence that it has been concentrated. It is still contained in the traps to the extent of a few hundredths of 1 per cent. Is it reasonable to suppose that solutions would dissolve out a constituent present in minute quantity and concentrate it to the amount of 50 to 100 times without having a notable effect in dissolving the minerals that are present in much larger quantity?

Those who favor the view of an ascending origin consider the Duluth gabbro, which is believed to underlie the whole region, as the source of the copper. Copper in small amount is associated with the small offshoots of this igneous body, and to those whose experience has led them to look upon intrusive bodies as a source of ore deposits this source seems adequate, favorably located, and probable.

TRANSPORTATION

Gravity circulation of solution is regarded as the transporting agent in the theory of descending origin. Doubt is thrown on the sufficiency of that method by the very slow rate of gravity circulation as indicated by the dryness of the deep levels of the mines and by the difficulty of conceiving a gravity circulation as operative far below sea level, as it must have been under conditions at all like the present. Moreover, the position of many of the ore shoots beneath relatively impermeable rocks seems inconsistent with deposition by descending solutions.

The view of concentration by diffusion avoids some of the difficulties of gravity circulation but meets others in explaining why copper was not concentrated equally in all lodes of similar physical character and chemical composition and why the ore occurs so definitely in shoots.

In the theory of ascending origin the medium of transportation is regarded as the solutions given off by the crystallizing magma of the Duluth gabbro. These were heated liquids or gases and therefore very mobile and were under high pressure, which could force them in quantity through rocks where gravity circulation would be practically nil. The solutions either entered the lodes by the direct connection of the downward extension of the lodes with the igneous mass or were led into the lodes through faults or fissures that extended to the igneous mass. This explanation seems to furnish an entirely adequate means of transportation and one entirely similar to that believed to have been active in the formation of most primary copper deposits.

CAUSE OF DEPOSITION

The theory of descending origin assumes that the copper was carried as an oxidized compound and was deposited through reduction by ferrous iron.

The conglomerates and amygdaloids were very rich in ferric iron and poor in ferrous iron long before the copper was introduced. Moreover, the alteration of the rock associated with the copper indicates that when the copper was deposited the ferric oxide was actually reduced and ferrous oxide added—a fact which shows pretty clearly that reduction by ferrous oxide was not the process that formed the copper.

The theory of ascending origin assumes that the solutions were such as ordinarily deposit sulphides and were essentially reducing and that if they had en countered rocks of the ordinary composition they would have deposited sulphides. But because these solutions encountered rock with a high content of ferric iron there were chemical changes before precipitation. Ferric iron was reduced, sulphur was oxidized, and native copper was formed. The lodes rich in ferric iron would be the places most favorable for the precipitation of copper.

OTHER RELATED DEPOSITS

There are throughout the world other deposits of native copper in which the copper appears to have been deposited as native metal and not to have been formed by surface oxidation of some other mineral, such as chalcocite. The chief examples of such deposits occur in Coro Coro, Bolivia; the Triassic areas of New Jersey and Connecticut; Cape d'Or, Nova Scotia; Oberstein, Germany; Commander Island, Russia; the Faroe Islands; Sao Paulo, Brazil; Upper Serbia; the Copper and White River districts, Alaska; the Comobabi Mountains, Arizona; Nova Zembla, Russia; and Coppermine River, Canada. The conditions of occurrence at these localities are set forth below:

Coro Coro, Bolivia.[41]—At Coro Coro occur the largest of a series of similar copper deposits that lie in a zone that extends across the Bolivian high plateau. The copper is found in the Puca red sandstone, of Cretaceous age, in both vein and bedded deposits. Mineralization has occurred at a number of closely spaced horizons. The dominant copper mineral is the native metal, although the sulphide chalcocite and the arsenide domeykite are sparingly developed. Native silver is also found associated with the copper. Oxides of copper occur at the surface but give way to the native metal, which persists at least to 380 meters, the greatest depth attained by the present workings. The sandstone, which away from the ore has a distinctly red color tone due to iron oxide or hydroxide, is bleached in the vicinity of the ore. The copper is thus usually surrounded by a halo of whitish or greenish rock that grades into the red which is the prevalent color of the formation away from ore.

At Coro Coro we evidently have the essential conditions to produce native copper from ascending sulphide solutions. None of the complications of lava flows as possible sources of copper, of ferrous minerals as possible reducers of oxidized copper solutions, nor of zeolites, prehnite, datolite, feldspar, or other associated minerals, that have served to cloud the situation in Michigan, are present. The evidence indicates that the solutions were ascending and that they were of the type that ordinarily would deposit sulphides. They encountered a highly oxidizing environment (red sandstone) and deposited native copper and native silver with considerable copper sulphide (chalcocite) and some arsenides. The rock surrounding the metals was bleached, and sulphates were deposited. The conditions are essentially those that are found in the conglomerate and sandstone lodes of Michigan.

Triassic of New Jersey.[42]—The Triassic of New Jersey consists mainly of characteristic red shale and sandstone but comprises also coarse conglomerate, black argillite, and gray or green flagstone. Both intrusive and extrusive rocks resembling the Lake Superior basalts in composition are also present. The main intrusive mass is that forming the Palisade diabase. The ore occurs in veins, which cut both igneous and sedimentary rocks, and disseminated in the sediments either just below the base of the effusive rocks or close to the dikes.

[41]Singewald, J. T., Johns Hopkins Univ. Studies in Geology No. 1, 1922.

[42]Lewis, J. V., State Geologist New Jersey Ann. Rept. for 1906, pp. 131-164, 1907.

The dominant copper mineral of the veins in the Palisade diabase is chalcopyrite. In the sediments close to intrusive rocks the copper occurs chiefly in chalcopyrite, bornite, and chalcocite, the native metal being absent. Away from the intrusive rocks native copper is the dominant ore mineral, although a little chalcocite is usually present.

Most of the native copper occurs in the red shale and sandstone just beneath the effusive rocks that constitute First Mountain. The deposit in the American mine, near Somerville, N. J., is typical of these occurrences. The ore bed is a purple rock with a texture between that of a fine-grained sandstone and a shale. This bed, which has been explored for a depth of 1,300 feet down the dip, is sparingly mineralized over a maximum thickness of 2½ feet. Wherever the copper occurs in this bed the rock has lost its purple color and is blanched to a pale gray or greenish white. Chalcocite is invariably associated with the native copper, which it apparently follows in age.

Triassic of Connecticut.[43]—In the central part of Connecticut basaltic flows, some of which show red amygdaloidal tops, are interbedded with the red Triassic sandstone and shale. At the Newgate prison, Simsbury, disseminated bornite occurs in the sandstone, whereas the near-by trap carries native copper. At Meriden a core of native copper is inclosed by a shell of chalcocite, thus indicating the chalcocite to be the younger mineral.

Cap d'Or, Nova Scotia.[44]—The native copper at Cap d'Or, Nova Scotia, according to Sir William Dawson, forms masses ranging from some several pounds in weight down to the most minute grains in the veins and fissures that traverse the trap, interbedded with the red Triassic sediments. The trap is amygdaloidal and carries various zeolites, such as analcite, natrolite, and chabazite. The deposits were examined by A. C. Lane, who found them strikingly like those at Lake Superior. Lane notes that the copper is found in veins that cut the lavas.

Oberstein, Germany.—At Oberstein, Germany, amygdaloidal basalts are interbedded with red sandstones and shales of Permian and Triassic age. In the amygdaloidal cavities of the basalts and in the red sediments a little disseminated native copper occurs. Fissures cutting the traps also contain narrow veins of chalcopyrite, with which are associated pyrite, calcite, prehnite, a boron mineral (datolite?), and analcite.

Commander Island, Russia.[45]—The deposits of Commander Island, Russia, are described at length by Morozewicz. The island consists of Tertiary effusive rocks belonging to the soda rhyolite family, overlain by andesitic and basaltic tuffs and breccias. The effusive and clastic rocks are cut by basaltic and andesitic dikes. The basaltic tuffs are described as being of a gray-green color and are cut by basaltic dikes. The copper occurs in both the tuffs and the dikes and is associated with zeolites. The order of mineral formation is given as iron oxide, calcite, analcite, and wire copper.

[43]Foye, W. G., personal communication, 1922.

[44]Dawson, William, Arcadian geology, 1878.

[45]Morozewicz, J., Com. géol. Mém., new ser., livr. 72, p. 44, 1912.

Faroe Islands.[46]—The Faroe Islands consist of late Tertiary basalts with which are associated red tuffs and volcanic breccias. Between some of the flows are red shaly layers carrying plant remains. Dikes and sills are rare, and marked faults are missing. The effusive rocks are typical amygdaloidal basalts, in which the amygdules are rich in zeolites. Native copper appears sparsely disseminated in the tops of the youngest as well as in the oldest of these flows. The copper-bearing amygdaloidal portion of the flows is of a violet-gray color. Associated with and apparently later than the copper are the zeolites, stilbite, and heulandite. The copper also occurs in the interstices of the breccias intimately associated with the cementing zeolites. At Suderoe the copper occurs in the amygdaloidal portion of a dense black trap. The amygdaloidal cavities carry stilbite, mesolite, heulandite, and a fluorine-bearing apophyllite, as well as copper; the copper seems to be the oldest of these minerals and is found upon the walls of the cavities. At Vaag the copper occurs as thin plates in a dark-brown tuff.

Sao Paulo, Brazil.[47]—In the State of Sao Paulo, Brazil, diabasic rocks occur as dikes and stocks and as flows interbedded with Permian sandstone and shale. The flows are amygdaloidal, their vesicles having been filled with zeolites, chalcedony, and calcite. At Sorocabana the brownish-black diabase shows flattened open spaces that are now lined with chalcedony and filled with a hydrous iron silicate. Native copper occurs at the boundary between these two minerals.

Upper Serbia.[48]—The native copper of Upper Serbia occurs in the vuggy openings of a hornblende andesite, which shows dacitic phases, together with chabazite, heulandite, stilbite, apophyllite, and calcite. The copper is incrusted with the zeolites. It is of the leaf variety, although crystals are also found. The copper occurs also in certain highly propylitized portions of the andesite; it is here associated with chabazite, heulandite, stilbite, opal, chalcedony, and calcite, which are younger than the copper.

White River, Alaska.[49]—The copper minerals on White River, Alaska, occur in interbedded effusive and pyroclastic rocks of Carboniferous age. Both sulphides and native copper are present. The lavas are slightly altered basalts of dark-brown, reddish, and green colors. The contact between two flows is as a rule easily determined because of a marked color difference. The copper minerals include both sulphide (usually chalcocite) and native copper; they are generally confined to the upper or amygdaloidal portions of the flows, although they also occur in veins and stringers. Associated with the copper minerals are zeolites, prehnite, quartz, and calcite. At the head of the Middle Fork of White River the country rock consists of stratiform basalts intercalated with beds of breccia and brick-red tuff. The native copper which occurs here is apparently limited to a certain definite volcanic sheet—a reddish lava, which is in places highly amygdaloidal. For 200 feet along the outcrop of the amygdaloidal rock metallic copper intergrown with prehnite, calcite, and zeolites can be found here and there in encouraging amounts. The copper occurs as irregular reticulating masses of metal several inches long and as small lumps and minute particles embedded in the minerals that line or fill vesicles in the lava flow.

[46]Cornu, F., Zeitschr. prakt. Geologie, 1907, p. 321.

[47]Hussak, E., Ueber das Vorkommen von gediegen Kupfer in den Diabasen von São Paulo: Centralbl. Mineralogie, 1906, pp. 333-335.

[48]Lazarevic, M., Zeitschr. prakt. Geologie, vol. 18, pp. 81-82, 1910.

[49]Knopf, Adolph, Econ. Geology, vol. 5, p. 247, 1910.

Copper River district, Alaska.[50]—In the Copper River district of Alaska the copper occurs in the pre-Triassic basaltic and andesitic rocks, which attain a thickness of more than 3,000 feet. The native metal occurs at different horizons in different parts of the district, but nowhere in encouraging amounts.

On Glacier Creek, a tributary to Chitistone River, the native metal, associated with chalcocite, occurs in a greenstone filled with black amygdules. Masses of native copper weighing several pounds are found, but the metal is present chiefly as small specks in the greenstone and the black amygdules and as paper-thin sheets or leaves.

On Fall Creek native copper occurs in a shattered grayish amygdaloidal greenstone. It forms small particles in both the altered and the seemingly unaltered greenstone and also in small veinlets of calcite and quartz.

On Nugget Creek a very little native copper occurs in the reddish, highly epidotized amygdaloidal portion of a basaltic flow. The copper is intimately associated with calcite and appears to be later than the chlorite, epidote, quartz, and prehnite.

Nova Zembla, Russia.[51]—The rocks of the Nova Zembla islands are interbedded limestones, conglomerates, and basaltic lavas. The basalt is in part intensely epidotized and is also cut by calcite and epidote veins. Both sulphides and native copper are disseminated in the amygdaloidal portions of the basalt and in veins. The native copper occurs in a red-brown brecciated top of gray-green or black basalt, which may locally be bright red owing to the presence of iron hydrate. The copper is deposited in the epidotized rock. Copper also occurs in a green augite porphyrite. The rock is strongly epidotized, and usually along with the copper this epidotization is marked, although abundant epidote does not always signify copper.

[50]Moffit, F. H., U. S. Geol. Survey Bull. 345, pp. 143, 168, 1908.

[51]Voit, F. W., Zeitschr. prakt. Geologie, vol. 21, p. 42, 1913.

Zwickau, Saxony.[52]—Native copper occurs in the red beds at Zwickau, Saxony. On both sides of minute copper veinlets the red rock is bleached yellowish owing to the reduction of the ferric hydroxide that colors the rocks.

Algodones, Chile.[53]—In the Mercedes mine, Algodones, Chile, a Mesozoic gray sandstone is cut by a diabase porphyry dike. In fractures in the dike there is a little native copper, with which a little native silver is associated. Native copper and cuprite in association with calcite and quartz replace propylitized portions of the rock, which is strongly impregnated with native copper. No ore appears to make in the sandstone. The amygdules of this dike rock contain calcite and delessite (?), and the mineral algodonite also occurs at this locality.

Comobabi Mountains, Arizona.[54]—In the eastern portion of the Comobabi Mountains, Arizona, there are lenses of altered greenish lava as much as 100 feet long, lying irregularly on lava. In this greenish lava quartz occurs as an alteration product of a red amygdaloidal basalt, and with the quartz in places there is native copper and cuprite. The altered rock that carries the copper is thoroughly epidotized and silicified. The amygdules usually show chlorite, epidote, quartz, and copper. The epidotized rock is cut by minute veinlets of quartz, epidote, and albite.

Permian "Red Beds" of the Southwest.[55]—In the "Red Beds" of the Southwest copper ore occurs in bituminous clay slate and marl in nuggets, nodules, or groups of irregular pockets, as carbonates, silicates, and siliceous carbonates. At Judge Kerr's farm, near Archer City, Tex., the green copper ore occurs in whitish-blue to dark-gray clays. At the Ball mine, about 7 miles northwest of Archer City, the ore consists of nodules and nuggets in a stiff white to gray bituminous clay slate or marl. This clay slate is interbedded with iron-rich clay and conglomerate. At the Isbell lead, half to three-quarters of a mile southeast of the Ball mine, the ore occurs as pseudomorphs after wood or as irregular lumps of black and green silicates in a slightly bituminous clay slate and marl.

In Oklahoma[56] the ore occurs as sulphide and as the native metal in the "Red Beds," consisting of sandstone and shale of a prevailingly red color. The sandstone is fine grained and ranges in color through white and yellow to red. The sulphide has locally replaced the woody material at a definite horizon. Among the sulphides observed were chalcocite and chalcopyrite. Azurite, malachite, and chalcanthite are also present. At Coldwater, Okla.,[57] the copper occurs as very thin sheets in a bed of red shale.

[52]Neues Jahrb., 1873, p. 64.

[53]Möricke, W., Die Gold- Silber- und Kupfer-Erzlagerstätten in Chile und ihre Abhängigkeit von Eruptivgesteinen: Naturf. Gesell. Freiburg im Breisgau Ber., Band 10, p. 180, 1897.

[54]Joralemon, I. B., report to Calumet & Arizona Copper Co.

[55]Schmitz, E. J., Am. Inst. Min. Eng. Trans., vol. 26, pp. 97-108, 1896.

[56]Tall, W. A., Econ. Geology, vol. 6, pp. 221-226, 1910.

In New Mexico[58] the ores occur not necessarily in the red beds that give rise to the name, but in the light-colored sandstones which are interbedded with them. The most conspicuous ores are malachite and azurite, but these are merely oxidation products of chalcocite. With the chalcocite are small quantities of bornite, pyrite, and chalcopyrite. Near Estey the chalcocite ore replaces the calcite cement of a 500-foot bed of red sandstone. The Copper Glance mine has sulphides, silicates, and carbonates of copper in a whitish, yellowish, or reddish sandstone. With the chalcocite a little hematite is associated. Of the copper minerals in the ore worked, about 60 per cent was chalcocite and about 40 per cent carbonate. About 5 per cent of the total copper content in most of the ore is present as native copper.

Montana.—Billingsley and Grimes[59] describe an occurrence of native copper at Copper Hill on Baggs Creek, east of Deer Lodge, Mont. Copper Hill consists of a series of lava flows, basaltic at the base but andesitic toward the top. Native copper in appreciable amounts is restricted to limited lenses within these flows. The metal occurs in the groundmass, in the augite phenocrysts, and in the amygdaloidal cavities, in the latter case with quartz, calcite, and zeolites (rare)." The authors consider the deposits due to a concentration by comparatively cool waters of copper originally widespread as a constituent (0.02 per cent or less) of the original rock.

Arctic Canada.—It has long been known that native copper occurs on the mainland and islands of northern Canada over a wide area. These deposits have been visited by a number of men, but the best accounts of them are one by Dr. James Douglas,[60] based on an examination and reports by George M. Douglas, Lionel Douglas, and August Sandberg, who examined the Coppermine River region in 1911, and one by J. J. O'Neill,[61] on the Arctic coast west of Kent Peninsula. The report by O'Neill reviews previous literature and contains maps showing what is known of the geology and geography of the region. The native copper occurs in a series of basaltic lavas interbedded with basic or amygdaloidal conglomerate.

[57]Haworth, Erasmus, and Bennett, John, Geol. Soc. America Bull., vol. 12, pp. 2-4, 1900.

[58]Lindgren, Waldemar, and others, U. S. Geol. Survey Prof. Paper 68, 1910.

[59]Billingsley, Paul, and Grimes, J. A., Ore deposits of the Boulder batholith, Mont.: Am. Inst. Min. Eng. Trans., vol. 58, p. 293, 1918.

[60]Canadian Min. Inst. Trans., vol. 16, pp. 83-144, 1913.

[61]Canadian Arctic expedition, 1913-1918, Rept., vol. 11, Geology and geography, pp. 1A-107A, 1924.

The regions about which most is known are those near Coppermine River and Bathurst Inlet. In the Coppermine River region, according to Sandberg, red rock occurs, and the rock associated with the copper is much altered. These conditions resemble those found in Michigan.

In bed No. 2 the rock, where exposed, has been very much altered in some places to epidote and a crumbling mass of light-colored rock, in which nearly all the amygdules contain copper carbonates. Native copper in the form of chips and flakes is fairly abundant in this altered rock.

In the Bathurst Inlet region the copper occurs disseminated in the traps, in the amygdaloids, and in fissures. Copper sulphide, principally chalcocite, has replaced dolomite underlying basalt, and chalcopyrite and chalcocite are disseminated in some of the sills or dikes of the region. Chalcocite also occurs in fissures in both regions.

O'Neill sums up the evidence on the origin of the deposits as follows:

FACTS FAVORING A SYNGENETIC ORIGIN

1. The apparently uniform distribution of native copper in individual flows of lava of large extent, and the occurrence of such flows throughout so extensive a district.

2. The copper is abundant in some flows and apparently absent from others.

3. The copper occurs minutely disseminated throughout the dense, massive part of the flows, as well as in the upper amygdaloidal parts.

4. In many places the rocks containing the copper are apparently fresh and unfissured.

5. In many instances copper occurs in the dense groundmass of a flow, while apparently none occurs in the amygdaloidal portion of the same flow.

6. Copper sulphides occur disseminated through massive sills of diabase, which probably came from the same magma as did the surface flows.

7. No enrichment of native copper has occurred in flows cut by sills of diabase, although the flows contain native copper and the sills sulphides of copper.

8.[62] On the Coppermine River conglomerates interbedded with copper-bearing lava flows carry native copper in the contained pebbles, but copper was not observed in the matrix by the Douglas party. The copper therefore must have been in the amygdaloid before the immediately overlying conglomerates were deposited.

FACTS FAVORING AN EPIGENETIC ORIGIN

1. Specimens of the copper-bearing flows examined under the microscope show that minute grains of native copper replace the matrix or some of the minerals of the rock.

2. Native copper forms the outer edge and in some cases the center of amygdules, and in some instances replaces other minerals of the amygdaloid filling.

3. In places native copper occurs in thin fissures and in veins in the flows, and at some places the copper was found to be more abundant nearer minute fissures than through the rest of the rock.

4. Chalcocite occurs in some of the veins in the flows.

5. Dolomites immediately underlying the copper-bearing basalts in many places have been partly replaced by chalcocite. The chalcocite is intimately mixed with covellite, so that it is probable that secondary enrichment has taken place to some extent.

6. At one place, on Iglor-u-allik Island, copper occurs about the contact of two of the flows of basalt. The lower foot of the upper flow contains considerable native copper, but no copper was seen throughout the rest of it.

7. A specimen of native copper in conglomerate was brought from the Coppermine River district to Dr. J. A. Allen, of the University of Alberta. The writer was shown this specimen and was immediately struck with the fact that the native copper in this case had replaced most of the matrix around the pebbles of amygdaloid.

[62]See also No. 7 under "Facts favoring an epigenetic origin."

APPLICATION OF GEOLOGY TO MINING

In the preceding pages and on the accompanying maps are presented in considerable detail the facts so far as they have been ascertained regarding the rocks of the district and the occurrence of the ores. The different theories of the way in which the ores were deposited have also been discussed. It has been hoped that both facts and theories would be of assistance in the search for new ore deposits.

This geologic report might perhaps wisely stop here and leave the practical application of its contents to be made by the mine operators of the district. Certain features that bear on the search for new ore, however, will be pointed out, but readers may draw their own conclusions, which may differ more or less from those presented in the following pages.

LIKELIHOOD OF FINDING NEW ORE BODIES

The advisability of searching for new ore bodies in the lodes is to be measured by the economic record of the ore bodies already mined and by the probability that similar bodies remain which can be found at reasonable cost. To the end of 1925 the mines of the district had paid in dividends about $290,000,000. It is safe to say that before the present known ore bodies are mined out and the companies liquidated, the dividends will be at least $400,000,000. There is no close record of capital expenditures, but from available data they are estimated at $150,000,000. It is apparent, therefore, that the district has yielded a fair profit, probably better than the average for mining districts. A large part of the dividends have come from operations on a few ore shoots, and the capital expenditures in developing these shoots have usually been small, so that the profits on these particular operations have been large. Most of the capital expenditures, however, have been made in developments that have paid nothing. In this respect the Michigan copper district does not differ from most other districts.

Granted that several ore shoots have yielded large profits, how likely is it that there are similar shoots in the district as yet undiscovered? Most of the bedrock in the district is covered with glacial drift and therefore not open to inspection, yet although some deposits have been found by accident, most of the ore shoots have been discovered on the outcrops or by old Indian workings that doubtless started on outcrops. Once a shoot has been located, extensions have been traced. An inspection of the geologic map will give an idea of the amount of development work done outside the ore bodies and make it clear that the thoroughly prospected area is but a small part of the total. There seems no doubt that undiscovered ore shoots exist.

That these shoots are not easy to discover is indicated by past experience. At best a rather large expenditure must be made before the success of an enterprise can be established. This, however, should not discourage those in a position to undertake such operations, as it is a condition that now prevails in practically all mining districts. In other districts, as truly as in this, most deposits easy of discovery have already been found.

CONDITIONS OF EXPLORATION

DRIFT COVERING

Much of the district is covered by glacial drift, which adds greatly to the expense of exploration everywhere and which over considerable areas, where it is several hundred feet thick, has to the present largely prohibited extensive exploration. Only the massive or otherwise resistant beds, such as the Greenstone flow, crop out prominently. The amygdaloids are relatively weak rocks and are ordinarily eroded somewhat below the traps and covered even where the traps are exposed. Though the lodes are rarely exposed, it has been mainly by exposures that the ore shoots have been found.

DISTRIBUTION OF DEPOSITS

The copper deposits are distributed stratigraphically through several thousand feet of rock, and geographically the main productive portion occupies a belt 2 to 4 miles wide extending from Central to Victoria, a distance of about 75 miles, though the larger part of the production to date has come from the central portion of this belt, about 40 miles in length. This belt is among the largest mineralized areas in the world.

The production since 1845 has been comparable to that from the Butte district since 1880, which has come from a few square miles. Most of the copper produced in the Michigan district has come from a few large deposits, but these are widely scattered, and the ore forms but a very small part of the rock within the mineralized area. The location of the ore bodies, even though large, in so extensive an area is, of course, relatively difficult.

GRADE OF ORE

All the lode deposits are of relatively low grade. The average yield for all lode deposits from the Champion mine north has been about 26.9 pounds to the ton, and from 1906 to 1923 the average for all mines of the district was about 21.5 pounds to the ton. If the Calumet & Hecla conglomerate is excluded, the average yield from the northern amygdaloid lodes has been 20.8 pounds to the ton from the beginning and 19.6 pounds from 1906 to 1923. Although the ore shoots are unusually large and regular as compared with those in other districts, nevertheless it is evident that in some the grade is not far above the economic limit, and a slight change in grade or in operating conditions suffices to put it below that limit.

After an ore shoot has been found, it is necessary to open a large mass of the lode to determine the size of the shoot and grade of the ore before it can be known whether or not a mine can be developed. To determine these questions is more difficult and costly in this district than in most others. The lodes must be opened by underground workings extending for thousands of feet, and mill tests must be made on the rock. Owing to the irregular distribution of the copper, no method of sampling that has been developed gives even a safe approximation of the grade of the ore. When the lode has been opened, those familiar with the ore can make a rough estimate of the copper content. If it is rich, the operators are warranted in going forward, but if it approaches the lower limit, only extensive mill tests will determine whether it is commercial or not.

In the past large sums have been expended in the development of shoots that proved to be below commercial grade, and it seems inevitable that this experience will be repeated in the future. It is not necessary, however, to erect an expensive mill in advance of proving a deposit, as has been done in some places in the past, for it is usually possible to make tests in existing mills, and in recent years this has been the custom.

SIZE OF DEPOSIT AND GRADE OF ORE

The belief is sometimes expressed that if ore of somewhat lower grade could be successfully mined, immense deposits would be available, but the increase would probably not be as great as is thought by some. Some ore shoots grade at the margins rather gradually into leaner and leaner ore, but it is far more common to go within a relatively short distance from profitable to hopelessly unprofitable ground. Within an ore shoot considerably more ground could be taken if the commercial grade were lowered.

It is perhaps common to think of high-grade deposits as necessarily small and of low-grade deposits as likely to be large. Whether or not there is any justification for such an idea as a general principle, it does not seem to hold good for the Michigan lode deposits. None of the great ore shoots have been mined out, nor are different shoots mined to the same extent, and therefore no final comparison is possible. Nevertheless there is a strong indication, as is suggested by the following table, that the larger shoots as measured by their content of copper, are consistently of the higher grade. The richer shoots have been most profitable and therefore most developed; if the leaner shoots had had the same amount of development they would probably show better than they do.

Yield from lode ore shoots through 1925

Shoot	Copper (pounds)		Dividends	
	Total	Per ton	Total	Per pound of copper (cents)
Calumet & Hecla conglomerate	3, 375, 000, 000	49. 07	$148, 700, 000	4. 41
Kearsarge	1, 177, 000, 000	19. 27	50, 880, 000	4. 32
Pewabic	873, 700, 000	22. 11	29, 242, 500	3. 35
Baltic	873, 000, 000	[a] 26. 50	43, 004, 000	4. 93
Osceola	416, 400, 000	16. 75	14, 700, 000	3. 55
Isle Royale	210, 800, 000	16. 39	2, 550, 000	1. 21
Atlantic	142, 800, 000	13. 55	990, 000	. 69
Mass	50, 000, 000	[b] 15	----------	----------
Superior	31, 000, 000	[b] 19	[c] 649, 000	2. 10
Victoria	20, 000, 000	[b] 12	----------	----------
White Pine	18, 000, 000	20. 3	33, 337. 50	. 18
Winona	17, 000, 000	[b] 14	----------	----------

[a] The high grade of the Baltic lode is due in part to sorting. [b] Approximate. [c] Includes final liquidation dividend, 1925.

It is apparent that the relation between grade and size of deposit as indicated by mining to date is not entirely consistent, and of course the actual size is undetermined. Nevertheless there is an unmistakable indication that the larger deposits are the higher in grade. If, then, a low-grade ore is encountered in prospecting, it should be developed to make sure that the openings are not in a poor spot in or on the margin of a richer shoot, but when it is once established that the shoot is of low grade, there is little reason to believe that it will make up in size what it lacks in richness.

SIZE AND GRADE NECESSARY FOR SUCCESS

The size and grade of a lode deposit necessary for success in operation will of course vary with conditions.

An inspection of the preceding table will show that in the past the profits have been roughly in proportion to the amount of ore mined and the grade of the deposits. As a rule, the lode deposits that have produced more than 100,000,000 pounds have been consistently profitable and those that have produced less have been rather consistently unprofitable, though the Superior and White Pine deposits, because of rather rich ore and other favorable conditions, have made earnings from a much smaller production. The lowest grade of ore that has generally been profitable in the past seems to be about 15 pounds to the ton, though the Atlantic shoot, which yielded a profit, averaged somewhat below that. It hardly need be said that relatively small mines located in rich parts of the large shoots, such as the South Kearsarge and Wolverine mines in the Kearsarge shoot, have been very profitable.

The profits from operations depend on many factors that will not be discussed here. The most detailed published discussion of the subject is one by Denton,[63] who reaches the following conclusion:

> It seems likely therefore that the minimum requirements for a profitable mine in one of our amygdaloids are, approximately, that 50 per cent of the lode must produce around 20 pounds per square foot of lode mined, concentrated into 1 ton of stamp rock. The mine one hopes for must show at least 60 per cent of the lode area producing 30 pounds of copper and 1 ton of stamp rock per square foot.

In other words, the minimum requirements where the rock is not sorted are that in one-half of the developed ground the lode must be 11 feet thick and yield 20 pounds of copper to the ton, and in the "mine one hopes for" 60 per cent of the developed ground must have a lode thickness of 11 feet and yield 30 pounds to to the ton. Where the rock is sorted the lode might be thicker and correspondingly leaner.

It is hardly necessary to say that an ore shoot must be considerably developed before any clear idea of the size and grade can be gathered. Where extensive development has been made on reasonably encouraging ground but failed to develop a mine, the resulting loss may be diminished by mining some of the best ground opened.

Fissures have yielded a comparatively small proportion of the copper and of the dividends for the district. In dividends per pound of copper, however, they compare favorably with lode deposits. The fissures that have proved profitable have been those that yielded mainly mass copper and, with the exception of the Mass fissure of the Ahmeek mine, were rich and profitable from the surface. In deposits of this class it was not necessary to open extensively in advance of profitable extraction, and the fissures that proved profitable were so almost from the start of operations. The fissures commonly contain a considerable amount of stamp rock, but those in which the copper was mainly in stamp rock have not been profitable. There are numerous fissures on the Keweenaw anticline that have been prospected but little or not at all, and the incentive for fissure exploration is much the same as that for lode exploration.

[63] Denton, F. W., Development and extraction methods for Lake Superior copper deposits: Lake Superior Min. Inst. Bull., August, 1922.

EXPLORATION OF LODES

Certain geologic conditions that have proved favorable to the formation of deposits may be briefly reviewed here in their bearing on exploration.

CHARACTER OF AMYGDALOID LODES

Amygdaloid lodes have been separated into four classes—cellular, cellular-coalescing, fragmental, and scoriaceous. The characteristics of these classes have been fully discussed in preceding sections and need not be restated here.

No mines or encouraging prospects have been developed in typical cellular amygdaloids, which appear unqualifiedly unfavorable. This applies equally to all cellular rock, whether the top of the flow is of that character throughout its extent or whether it is fragmental in places and cellular in places.

The fact that the lode is fragmental in one place increases the probability that it may be fragmental in other places. All but two of the largely productive amygdaloids of the district and most of those that have given some encouragement are of the fragmental type. There seems no doubt that this is the most favorable type. The fragmental amygdaloids form not more than 10 to 15 per cent of the total, and cellular amygdaloids make up most of the remainder. It is evident, therefore, that the physical character of the amygdaloids affords criteria by which a large proportion can be eliminated.

A considerable proportion of the copper from the Pewabic amygdaloid lodes of the Quincy mine has come from cellular-coalescing rock, though the lodes are in part fragmental. There is no doubt that valuable deposits can and do occur in the cellular-coalescing lodes.

The Ashbed is the only scoriaceous lode in which shoots have been opened. The Atlantic mine is the only deposit in the Ashbed that has been profitable, and that not largely so. It is evidently possible for the lodes of the scoriaceous type to be mineralized to the extent of containing profitable shoots, but they are pretty clearly on the border line between favorable and unfavorable.

The influence of hematite in causing the precipitation of metallic copper indicates that highly oxidized lodes are the most favorable for ore deposition. The same influences that tend to form fragmental lodes seem to cause high oxidation, so that in the main the lodes that are physically favorable are also chemically favorable. It may be pointed out, therefore, that cellular amygdaloid that is highly oxidized may be more likely to pass into fragmental amygdaloid than that which is poorly oxidized.

CONGLOMERATES

Only two of the several conglomerates of the district have been shown to be extensively mineralized, namely, the Calumet & Hecla, and the Allouez. Both, where mineralized, are moderately coarse, and the Calumet & Hecla conglomerate, where it thins and changes to sandstone, quickly decreases in copper content. It appears that a moderately coarse conglomerate has the permeability requisite for forming an ore deposit. It seems probable that a moderately thin conglomerate that pinches out in places along the strike but is continuous down the dip is more favorable than a thick conglomerate continuous for long stretches that gives no opportunity for convergence of rising solutions. All the conglomerates have relatively abundant ferric oxide and are in this respect apparently chemically favorable to copper deposition.

The sandstone of the Nonesuch formation at the White Pine mine and neighboring prospects is the only sandstone known to be strongly mineralized and that is mineralized only relatively near to fissures. Sandstone therefore does not seem to be favorable to mineralization, though it is of course more favorable than shale.

MINERALOGY AS A GUIDE IN EXPLORATION AND DEVELOPMENT

A detailed study of the mineralogy and paragenesis of minerals has been a feature of all the more comprehensive geologic studies of the district, starting with Pumpelly's work and continuing through the present investigation. One of the objects of these mineralogic studies has been to find, if possible, minerals that would serve as indications of either the presence or the absence of copper in their neighborhood. It may be said at the start that these studies have not developed any very positive aids in either the general exploration stages or the later development and mining stages.

Mineralogic features, like textural features, are largely of local occurrence, and the best of ore shoots are known to contain patches of minerals that are regarded as unfavorable indications of copper; likewise many amygdaloids which so far as known contain no ore shoots may for long distances carry mineral combinations that are characteristic of some of the big ore shoots in the district. In the later stages of development observation of the copper itself is a better indication of the grade of the ground than a study of the gangue minerals.

MINERALOGIC GUIDES IN AMYGDALOIDS

The principal minerals that are regarded favorably as indications of copper in amygdaloids are the quartz-pumpellyite-epidote combination which is associated with copper, especially in the Isle Royale, Baltic, Pewabic, and Evergreen lodes. However, many impermeable cellular amygdaloids that show alteration of this type are encountered in diamond drilling and crosscutting. The presence of these minerals should not lead to more extensive examination by underground openings unless other features, such as favorable physical character of rock or presence of copper, give additional cause for encouragement.

The rock bleached through the removal of iron, on the other hand, is much more rare and, so far as known, is invariably accompanied by copper. Furthermore, there is a distinct feeling that this bleached rock is indicative of a rather intense degree of mineralization, so that if a drill hole or a crosscut encounters a little copper surrounded by bleached rock, it is regarded more favorably than a similar quantity of copper without the bleached rock.

Red feldspar, prehnite, and datolite are to be regarded as more favorable than otherwise. The prehnite usually has some fine copper associated with it though prehnitized areas in the Osceola lode are rather poor. In general a fragmental lode showing these minerals, with perhaps some epidote and pumpellyite, is to be regarded more favorably than a lode of the same type with nothing but calcite in the interfragmental spaces. What probably amounts to the same thing is that the greater the variety of minerals the more favorable the appearance of the lode. Most of the commercial lodes have a greater variety of minerals than the average amygdaloid.

Calcite and chlorite are rather indecisive indicators. The intense chloritization in some places, such as adjacent to fissures in the Kearsarge lode and in the shattered areas near the Keweenaw fault, would seem to be an unfavorable sign.

Laumontite is generally regarded unfavorably. However, there are local patches of lean laumontitized rock in the best ore shoots.

The value of copper itself as an indication of an ore shoot needs some discussion. If copper is present in a drill core from an amygdaloid, it is of course always encouraging, but it is more encouraging under certain conditions than under others. The most favorable mode of occurrence is in association with rock bleached by the removal of iron in a fragmental amygdaloid. Copper associated with the pumpellyite-quartz-epidote combination is also favorable, especially if in a fragmental lode.

Copper in a fragmental lode leads to interest in the lode at that point, whereas copper in some quantity in a cellular lode encourages examination of that lode elsewhere to see if it changes into one of more favorable character, such as a coalescing cellular lode or a fragmental lode. Very fine copper in prehnite or calcite is pretty common and not very encouraging. Copper in small seams in amygdaloids of any type is in general of little interest.

MINERALOGIC GUIDES IN CONGLOMERATES

The variety of introduced minerals in conglomerates is much less than in amygdaloids, but in general the same principles apply to the use of mineralogy in exploring and developing rock of both types. Many of the conglomerates seen in drill cores have practically none of these minerals, with the exception of a little calcite. As in the amygdaloids, the occurrence of rock bleached by iron removal as a rule probably indicates copper mineralization. Likewise, it is probable that a greater variety of secondary minerals in a conglomerate is a better indication than calcite alone.

MINERALOGIC GUIDES IN FISSURES

Little if any choice between two fissures can be made on the basis of mineralogy. The chief gangue mineral in the Mass fissure at the Ahmeek mine is calcite. The Owl Creek fissure at the Copper Falls mine in places had an abundance of datolite. Prehnite is common in many of the fissures of Keweenaw County. Some of the barren "crossings" in the lodes of the district are said to be mainly calcite. In many places the Mass fissure at the Ahmeek mine is merely a chlorite seam. In general, other things being equal, a fissure with a variety of gangue minerals is more encouraging than one with only a few.

In summary, although mineralogy is of value in exploration, its use must be accompanied by an understanding of its limitations. Some of the limitations are indicated. The best sign of copper is copper itself and the occurrence of copper in favorable lode rock is a much better sign than all the gangue minerals without copper in unfavorable rock. In development and mining mineralogy is of less use. In these operations the copper itself as seen in the openings is the best guide.

ORE SHOOTS

EXTENT OF LODES

In several of the lodes it is pretty clear that the ore-forming solutions have traveled upward for long distances in the lodes themselves. It may thus be assumed that a long downward extension of permeable lode is essential to the formation of an ore shoot. It might be supposed that long downward extension would accompany long lateral extension of flows and that therefore the relatively thick flows extending for long distances along the strike would be most favorable. There is some support for this idea in the fact that the Kearsarge, Osceola, and Baltic are all relatively thick flows and that the first two are known for long distances along the strike. The individual flows of the Pewabic amygdaloid are relatively thin and apparently not continuous for long distances. However, if the flows came from the central part of the basin, any that reach the present outcrop may be assumed to extend a long distance down the dip. It is questionable, therefore, whether thickness of flow should be given any weight in the matter of favor-ability.

BARRIERS

The concentrating effect of barriers is fully discussed on page 115.

Barriers in the lode itself.—There are two general conditions in the lodes themselves favorable to concentration of solutions—(*a*) a lode that is prevailingly impermeable but contains permeable areas having a long downward extension; (*B*) a lode that is prevailingly permeable but contains bars of impermeable rock so placed as to cause a concentration of rising solutions. The Calumet & Hecla conglomerate and the Kearsarge amygdaloid are examples of the first type, and the Osceola lode of the second. Recognition of the first type should be of help in prospecting. In the second type, where the barrier in the lode is relatively small, it is probably quite as easy to find the ore shoot itself as it is to find the barrier. In the development of an ore shoot once found, however, the recognition of the barrier should be of decided help.

Folds.—It would be expected that solutions rising along a lode would tend to concentrate near the crests of the anticlinal folds that extend down the dip transverse to the general strike of the rocks. The presence of ore shoots on the Allouez, Baltic, Winona, Mass, and Michigan anticlines lends support to this idea. On the other hand, there are several deposits, such as the Calumet & Hecla conglomerate, Osceola, and Quincy, that are not on folds, and the Isle Royale and Forest ("Victoria") are on synclines. In the shoots studied in detail that are on anticlines the distribution of copper is more closely related to I the character of the lode rock than to the crest of the anticline. The positions of the anticlines are well known, and if the idea proves to have any merit it can be easily applied.

Faults.—A fault offsetting a lode and making an angle with the dip of the lode would be a barrier that would tend to concentrate rising solutions the same as impermeable rock. Many faults are known that have sufficient throw to produce this effect, and there are doubtless many small unknown faults that might have this influence.

FISSURE DEPOSITS

The ore shoots in several fissures are at or near the intersection with thick, well-oxidized amygdaloids or conglomerates, and around the Keweenaw anticline they occur under the Allouez "slide," which probably acted as a barrier. These relations should be kept in mind in the prospecting of fissures.

GEOLOGIC DISTRIBUTION

The ore deposits in general are distributed geologically from a horizon near the lowest exposed part of the series to one well toward the top of the portion where flows predominate. The deposits in the Nonesuch formation are much higher but so far as known are present only near the Porcupine Mountain dome. There seems to be no very systematic arrangement in the geologic horizons at which the deposits occur. Near the central portion of the district, in a relatively short stretch from Quincy to Baltic, lodes occur from the highest to the lowest and at intermediate horizons. To the north the largely productive lodes are at intermediate horizons, though the Ashbed high in the series has been productive well to the north, at Copper Falls. In the south end of the district the productive lodes have been mainly near No. 8 conglomerate, at an intermediate horizon. From the distribution of the known deposits there seems little reason for favoring one horizon in the series over another.

GEOGRAPHIC DISTRIBUTION

Geographically the most productive part of the district, from Champion to Mohawk, is centrally located. Lode production greatly predominates in this central portion. North of the more highly productive area there has been considerable output from fissures, and south of it from both lodes and fissures. There is some reason to think that mineralization decreases in amount north and south of the central area, but it is not to be supposed that the commercial limits are those indicated by the present profitable lode mines.

The assertion frequently made that only one deposit occurs in any section across the mineralized belt is not wholly supported by the facts. The Calumet & Hecla conglomerate and Osceola shoots in part overlap. The Allouez conglomerate is mineralized and was mined above the Kearsarge shoot. The Atlantic in part overlies the Isle Royale and Superior. The Quincy has mined several lodes in the same section, and in the south end of the district the same is true of operations on the Evergreen and succeeding lodes. There seems no good reason for considering that an area is distinctly less promising because an ore shoot has already been developed in the cross section of the belt in which the area lies or that a section in which no ore shoot has been developed is particularly promising for that reason alone.

In no lode, up to the present time, have two widely separated profitable ore shoots been developed. Widely separated shoots have been developed in the Ashbed, in the Allouez conglomerate, and in the Evergreen and succeeding lodes of that series, but not more than one of those in a given lode has been profitable. There seems, then, to be no basis for supposing that a horizon at which productive deposits have been found in one part of the district is a particularly favorable horizon for prospecting in another part far distant, nor for prospecting a well-known and productive lode at a place far from an area where it is known to be productive, unless at this place it shows favorable character and signs of mineralization. Prospecting of well-known lodes at a distance from areas where they are known to be productive has been pretty thoroughly tried, and to the present time it has consistently resulted in failure. There seems no reason, however, why a lode should not contain more than one ore shoot, and if it is favorable in character at a distance from the known shoot, it should be considered as attentively as other equally favorable lodes. If it is physically unfavorable, on the other hand, it deserves no more attention than other unfavorable lodes.

In short, a given lode at a given place should be treated according to the local indications, and no money and effort should be expended on the basis of what the same lode may contain 20 miles away.

RELATION TO PRESENT SURFACE

All known important deposits appear to have reached the surface and to have been as rich at some places along the outcrop as at any greater depth. (See p. 112.) It would seem, therefore, that in prospecting the chance of striking a shoot at the richest point is probably as good at one depth as at another within practical limits. The depth at which general exploration should be carried on should be governed by the cost at the particular place considered. In new territory relatively shallow depth will usually be cheapest. Near old mines deeper exploration from existing openings may be just as cheap, and the deep openings may develop much less water and thus cause less future expense in pumping in case the prospect is abandoned. It is of course to be recognized that exploration for known or supposed shoots entering a property at depth constitutes a special case.

EXPLORATION

STAGES

Exploration in the Copper Range has now been in progress for more than 75 years and in different places has reached very different stages in its progress toward what may be regarded as complete exploration. For the portion of the range in Wisconsin the Wisconsin Geological Survey has now in progress the outlining of the broader geologic relations. For small areas in Michigan very detailed information is available. All stages between those extremes are to be found.

The problem to be solved in any given area and the method of attacking it depend on the information already in hand. In an area of which little is known the effective method is to proceed from the more general type of information to the more detailed. Lode exploration may be efficiently conducted in the following general order: (1) Geologic reconnaissance; (2) location of favorable lodes; (3) search for ore shoots; (4) development of prospects; (5) development of known ore bodies.

Geologic reconnaissance.—For most of the copper belt of Michigan the early stage has been passed, and the general distribution and relations of the rocks are known. Near the end of Keweenaw Point and toward the Wisconsin boundary there is still something to be gained from work of this type.

Location of favorable lodes.—With the general location and geologic relations determined, the next step is to find what are regarded as favorable lodes and conversely to determine unfavorable lodes.

For the area between Victoria and Breakfast Lake the accompanying geologic maps and sections give the character of the lodes and their position so far as known. For some areas this information is rather detailed, but for others it is very slight. It is evident that much remains to be done in this stage of exploration.

Search for ore shoots.—As is well known, no lode is mineralized to a commercial degree over more than a small part of its extent. Moreover, numerous beds that have all the properties that are regarded as favorable to mineralization are not known to contain minable ore at any place, though no lode has been thoroughly tested throughout. It is clear that the copper occurs in distinct shoots, only the larger and richer of which are of commercial importance.

It is always possible that a shoot may be discovered at any stage of exploration, and as a matter of fact most of those now known have been located in the early stages or entirely by chance. The probability of locating additional shoots by finding outcrops containing copper or by following up old Indian diggings is not great. Ore shoots are likely to be found in the future only by systematic search, implying an exploration program and the use of methods materially different from those that were cheapest in earlier stages.

Development of prospects.—Once a stretch of lode that contains an encouraging amount of copper is located, it must be developed to determine whether or not it is of a size and grade to make a mine. At this stage in particular an understanding of the behavior of the shoots in the developed mines is likely to be of assistance.

Exploration of ore shoots.—The mining of the great ore bodies, if it is to be carried out efficiently, must be planned far ahead of actual operation. The determination of the probable position and extent of a known ore shoot in undeveloped ground is an important function of exploration.

METHODS OF EXPLORATION

The several methods of exploration that have been commonly applied in the region, usually in the order named, are (1) examination and mapping of surface exposures; (2) trenching or digging test pits where the overburden is shallow; (3) diamond drilling; (4) underground openings. Other methods have been tried on a far less extensive scale.

Examination of surface.—To get all the information that is possible from an examination of the surface is of course the first step in exploration work at any stage. It was early applied and resulted in outlining the broader features of the geology which have long been known. This method is particularly useful in the reconnaissance stages of exploration but may also be useful in later stages. Considerable detailed information may thus be obtained for small areas, especially along stretches of lake shore and along river channels. Elsewhere only the more resistant beds are commonly exposed, and the amygdaloids, which are weak and easily eroded, usually occupy relatively depressed areas and are therefore commonly covered.

Trenches and pits.—The results obtained by digging trenches and pits in exploration are of course dependent on depth and character of overburden and on water conditions. In general this method is practicable only in areas covered by a few feet of overburden and is not applicable to swampy areas even where the overburden is thin. Wherever it can be effectively applied, this method is useful in all the earlier stages of exploration—namely, geologic reconnaissance, location of favorable lodes, and search for ore shoots.

Diamond drilling.—Diamond drilling has been employed in exploration in the copper country since 1882 and has probably furnished more detailed geologic information than all other methods combined. It is highly effective in determining the character of flows for general correlation, and where skillfully conducted it has proved very useful in determining the character of lodes. The medium-sized 1⅛-inch core from the “A” bit is much more informing than the ⅞-inch core from the “E” bit and is well worth the difference in cost. Although diamond drilling is the most efficient method of getting information as to the kind of rocks and the character and position of lodes where outcrops or surface trenching will not furnish this information, the diamond drill has proved of rather doubtful service in the search for ore shoots. Owing to the very irregular distribution of copper in the average amygdaloid lode, a drill-core sample is likely to be equally misleading whether it contains copper or not, though the presence of copper should, of course, always be regarded as encouraging. Cores sufficiently encouraging to cause the sinking of exploratory shafts have been obtained at several places, as Mandan, Ojibway, Mayflower-Old Colony, and St. Louis, where disappointing results were encountered when the lodes were opened. The Lake lode, on the other hand, was located by diamond drilling and proved sufficiently mineralized to lead to rather extensive development. At the New Arcadian mine the lode that showed best in the drilling proved disappointing, but a near-by lode that was opened in the underground exploration has been extensively developed. Diamond drilling is thus a far less reliable guide in the search for ore shoots than trenching or underground openings, methods by which it is advisable, where indications warrant the expense, to expose considerable portions of the potential lode. Obviously, however, the information as to copper content obtained by diamond drilling is not to be neglected. Drill-core samples are more nearly representative of conglomerates than of amygdaloids, because the copper is more evenly distributed in the former rock than in the latter. The uniformity of distribution and the consequent reliability of drill-core samples is naturally even greater for finer sediments; the cores have been shown to give the copper content of the Nonesuch sandstone and shale, for example, with a fair degree of accuracy.

The diamond drill has been used rather extensively in some mines to locate copper ground in known lodes. It has been used most in the Quincy mine, where the lode is of the coalescing type, and for that type it is said to be effective. It was also used in the Osceola mine to locate “foot lode” copper, but here it produced; rather indifferent results and was given up. In the average amygdaloid lode the advisability of its use for this purpose seems open to question.

Foot for foot, diamond drilling is, of course, much cheaper than underground opening. Probably at least 4 feet of drilling can be done at the cost of 1 foot of underground opening. In cross-sectioning inclined beds the ratio is even more favorable to the drill, which can cut the beds at right angles and traverse a given stratigraphic thickness with a minimum footage, as a crosscut can rarely do. It may thus be possible to section a lode or series of lodes several times with the diamond drill at the same cost as a single section with an underground opening.

Churn drilling.—Churn drilling, so far as known has been used only at the Laurium property. The records of this work do not indicate that it is effective in giving any type of information in this district, and drill cuttings must obviously be far less informing than a core. The churn drill might be effective in drilling through overburden to bedrock.

Underground opening.—Underground opening, of course, gives, foot for foot, the most satisfactory information of all kinds. For general geologic information or the location of favorable lodes it is ordinarily too expensive. In the search for ore shoots where trenching is not practicable it is probably the most effective method. In the development of prospects it is the only effective means of determining the position of the ore shoot and the copper content of the ground.

Other methods.—The dip needle has been employed by the Wisconsin Geological Survey in working out the general distribution and structure of the copper-bearing rocks. This method has been but relatively little employed in the Michigan copper district, and for much of the area more detailed data are already available than are likely to result from dip-needle work alone.

For certain problems, even in the more intensively developed areas, the dip needle will furnish geologic data at a lower cost than most other methods. In the less developed areas it has a larger field of usefulness. The possibilities of the use of the dip needle are discussed in the section on geophysical methods (pp. 156-168). Other geophysical methods have been but little used in the Copper Range. Electrical methods have been tried as outlined on pages 158-160 but have given as yet no very encouraging results.

APPLICATION OF METHODS

The results attained with a given amount of money vary considerably with the skill used in choosing and applying the different means of exploration, even when the simplest methods are employed.

SURFACE EXAMINATION

A careful determination of the type and grain of the traps may give considerable information on the thickness and correlation of beds that are only slightly exposed and thus save more expensive work by restricting trenching and drilling to the vicinity of flow tops.

TRENCHING

In trenching across the strike of flows, if the grain of the rock is determined, it is possible to judge the approximate thickness of many flows and to avoid continuous trenching over the central portion of such flows.

DIAMOND DRILLING

Diamond drilling has been pretty thoroughly developed and systematized in the district, but there are certain features that may well be emphasized.

In making cross sections it is the general practice to drill the section across the supposed strike and, unless there are special reasons for doing otherwise, at nearly right angles to the supposed dip of the beds. This of course gives the maximum section for a given footage. It is worth going to considerable trouble, if necessary, to determine the strike of the beds before starting an extensive cross section. The purpose of a cross section is to determine not only the character of the beds but their attitude, and for this purpose a correlation between two holes is necessary. It is desirable, therefore, to find a characteristic bed that will permit correlation near the bottom of the hole farthest down the dip and to cut this same bed near the top of the next hole up the dip. It is well worth while to carry a hole some distance beyond what would otherwise be the most economical limit in length or to stop it short of that limit if such a correlation can be effected. A sedimentary bed is usually the best for correlation, but certain characteristic flows are satisfactory.

If beds of favorable character are encountered near the bottom of a hole, it is worth while to cut these in the next hole to determine their character at another point. To accomplish this, a hole may be stopped short of the most economic length after passing through favorable amygdaloids in order to start the next hole near the outcrop of those beds and cub them again.

Both the “A” bit, with 1⅛-inch core, and the “E” bit, with ⅞-inch core, have been used in the district. The “A” bit has given a far better core recovery, especially of the amygdaloids, and therefore a better idea of the beds, and this advantage is well worth the difference in cost of operation. Larger bits have been used, but except under special conditions they are probably not justified by the additional information obtained.

A careful record should be made of every hole at the time of drilling, but in addition the core should be preserved, so that it can be reexamined when desired. A core may be stored at a cost of but a few cents a foot, and there is no justification for not preserving it. A few suggestions resulting from the examination of many thousand feet of core may not be out of place.

Cores are usually, stored in wooden boxes ranging from 5 to 9 feet in length and containing from five to eight or nine rows of core each. The rows of core are commonly separated by wooden dividers. The size of box is not material, but pine lumber, even of poor quality, is preferable to even high-grade hemlock. Sheet zinc may be used for dividers in place of wood strips. This saves some space, and the cost per foot of core is about the same.

Marking of the depths within the box and marking of the box are highly important. For marking depths, 1-inch wooden blocks the width of the core should be used. The depth should be clearly marked in pencil on the top and one side of the block. A block should be placed at the end of each pull. It is convenient if the beginning of the box is marked with an arrow, and it is advisable to follow the general custom of placing the cores so that they are to be read from left to right as a book is read. Red marks on the dividing strips opposite places where copper is found in the core are helpful. The box, not the cover, should be marked both inside and outside with the name of the property, the number of the hole, and the depth. Metal tags with the numbers and letters stamped on are durable, but the box itself should be marked in addition.

Cores should be stored in a dry place and piled well above the ground. If left out of doors or in a leaky building, they might as well be thrown out at once, as the boxes will soon be decayed. (See pl. 54, B.)

Some years ago the Michigan Geological Survey, recognizing that the matter was one of public interest, undertook to preserve such cores as were not being cared for by the companies. Unfortunately this effort was not continued, and those already collected were not given proper care.

UNDERGROUND EXPLORATION

Depth.—The first question to determine in exploration is the most favorable depth. As an ore shoot is as likely to be found at one depth as another (see p. 112), the depth of exploration depends on the cost, and in most places the most economical depth would probably be shallow.

Horizontal versus vertical exploration.—In many of the explorations in the district, shafts have been sunk to a depth of 1,000 to 2,000 feet, and the vertical element of exploration has been emphasized, as contrasted with exploration along the lodes. Whether the chance of encountering an ore shoot will be greatest by opening down the dip of a lode or along the strike will depend on the attitude of the ore shoot. If the shoot extends directly down the dip, exploration in that direction will be least effective and drifting along the lode most effective, but if the shoot is horizontal the reverse will be true. Most of the known shoots trend more nearly with the dip of the lodes than with the strike, and therefore, in general, drifting should be preferable to sinking. Drifting, moreover, has the advantage of being cheaper; it also affords the easier method of following an irregular lode and of testing any lode by crosscuts.

If encouraging results are not encountered at one level, it is very questionable whether drifting at another level is justified in general prospecting, but if the extension of a known shoot is being sought, drifting at another level may be desirable.

Examples are cited in the discussion of ore shoots where a lode is poor in stretches near the surface and richer at depth, but as a rule drifting along the lode would have encountered the rich shoots with less effort than opening down the lode.

If an encouraging amount of copper is encountered, it is of course worth while to open the shoot down the dip as well as along the strike, but it is desirable to follow the shoot along the strike to its limits on each level opened in order to get the horizontal extent and probable attitude as early as possible. If a lode is rich, it is common practice to run levels in it during development, at the regular operating intervals of 125 to 150 feet. If the deposit is of doubtful grade or size perhaps the more common and better practice is to open it only at considerably greater intervals; the probable extent and grade are thus determined at a lower cost.

Transverse versus longitudinal exploration.—In past exploration two practices have been more or less consistently followed—the examination of a lode or lodes known to be mineralized elswhere in the district, to the exclusion of the other lodes; and a preliminary cross sectioning of all the lodes in an area by diamond drill, trench, or crosscut and the further examination of any encouraging lodes that may be found. The information already available for much of the district gives a general idea of the character of the beds, from which it can be judged what method is likely to give the best results. Crosscutting would usually be employed where it is desired to investigate several adjacent lodes that are known to be of favorable character. If, on the other hand, diamond drilling has shown a promising lode in a series of unfavorable lodes the promising lode would of course be best t examined by itself.

Prospecting fissures.—It has been pointed out that many of the known fissure deposits occur at the intersection of fissures with strong lodes and also that they may be under barriers like the Allouez "slide." These, then, are the places to be specially examined by the method that local conditions render easiest.

Where fissures are closely spaced it may be advantageous to drift on a strong amygdaloid across a number of such fissures, further developing any that show promise. Where they are widely spaced it will probably be advantageous to examine each fissure separately.

Equipment for prospecting.—It is obvious that no prospect in its earliest stages of development justifies the assumption that it will be a mine. Therefore, until a prospect is pretty well proved the equipment and the openings should be the cheapest that can be effectively employed. Certainly the building of a mill should wait till the ore for it is fully assured. Such a policy may lead to slight losses in the relatively few prospects that develop into mines, but the owners of such properties can stand the loss.

SUGGESTIONS FOR FUTURE GEOLOGIC WORK IN THE COPPER RANGE

The present report is but one of a series that have been made during the last 75 years. Each of the reports recorded the available facts concerning the geology of the district and expressed the opinions of the authors regarding the occurrence of the ores. With each succeeding report there has been a growing body of facts and a changing view regarding the occurrence of the ores. The change in view has been influenced by the accumulating facts, by the general increase in knowledge of ore deposits, and of course by the views of the different individuals who have been engaged in the several investigations.

Each of the previous reports has been helpful in the development of the district, and it is hoped that this one will also be helpful. The authors o f the report probably realize more keenly than others its shortcomings, and they are well aware how much remains to be done and how important the continuance of geologic work in the district is likely to be. Many of the problems can be solved only by a steady, persistent collection and correlation of data from year to year, and the necessity for this work will not cease till mining in the district is definitely abandoned.

One of the first necessities for a geologic study is an accurate base map. A modern topographic map has been prepared for the central part of the copper district in Michigan, but this should be extended over the district as a base for accurately recording geologic data.

The district presents numerous geologic problems that are still unsolved or only partly solved. Among these are the problem of the Keweenaw fault and the associated problems, such as the depth and attitude of the Keweenawan lavas beneath the "Eastern" sandstone, and whether or not they contain valuable copper deposits east of the Keweenaw fault. Solution of these problems will involve the study of the South Trap Range and its relation to the Copper Range.

The Porcupine Mountain area, the portion of the Copper Range westward from the Victoria mine to the Wisconsin boundary, and the area near the end of Keweenaw Point, in Keweenaw County, are but little known. Throughout the district, in fact, there are rather large areas of which little is known, as can be seen by inspection of the maps. Much can doubtless be done toward filling these gaps by magnetic surveys and other relatively cheap methods. This work should be done on a scale and with an accuracy suitable to use in mining development. Much trenching and other exploration was carried on in the early days, especially in Keweenaw County, of which there is no record. The location of these openings on an accurate base map would give considerable information as to what has already been done and as to localities where additional exploration is most promising. In this same area there is considerable to be done in mapping outcrops when a suitable base map is available.

It is already demonstrated that dip-needle mapping of the formations can be carried on to advantage, and there is a considerable field for this work in further mapping of the general geology.

The possibility of the development and application of geophysical methods to the search for ore in the district should be kept constantly in mind. The fact that they have not been notably helpful to the present time should not discourage the study of such methods.

Likewise there should be a continuing study of the ore occurrences with the purpose of discovering additional guides to the search for ore. Progress has been made in this direction over a period of 75 years, and it is clear that the end has not yet been reached.

To summarize, it may be stated that what is needed in this as in every other mining district is continuous geologic work with an accurate record and correlation of all data relating to the occurrence of ores and the steady and persistent attempt to apply new knowledge and new methods to the finding of new ore bodies and the exploration of those already known.

GEOPHYSICAL METHODS APPLIED TO EXPLORATION AND GEOLOGIC MAPPING
By T. M. Broderick and C. D. Hohl

INTRODUCTION

USE OF GEOPHYSICAL METHODS

During the last few years considerable interest has been aroused in the application of geophysical methods to the search for economic minerals. Well-authenticated cases of the discovery of deposits so diverse as iron ore, copper sulphide deposits, gold veins, and oil pools, either directly or indirectly as a result of the use of these methods, are on record. The recent wide spread interest in this subject is the outcome of the rapid development of the methods in the last decade, particularly in Germany, Sweden, and France.

One type of geophysical observation has long been known and used in the Lake Superior region. Every geologist in the iron districts regards the magnetic dip needle as an essential part of his equipment, and a “magnetic survey” is in by far the greater number of explorations one of the first steps. Curiously enough, however, the possibilities of magnetic observations, regarded as essential in geologic mapping in the iron districts of the adjacent counties, were practically ignored in the copper country. It is safe to say that the present high degree of completeness of knowledge of the stratigraphy in this district could have been obtained at an enormous saving had magnetic surveying been used in the explorations of the old type. Thousands of feet of diamond drilling and trenching could have been dispensed with, preliminary shafts and crosscuts, poking around to “find the lode,” would have been unnecessary, many miles of expensive transit work on the surface could have been saved, and mines such as the Ahmeek and Mohawk, long undiscovered because of a simple curvature in the strike of the lode, would have been found as soon as anyone with a dip needle had taken the trouble to work along the strike from the original discovery. However, the results were obtained, even though at unnecessary expense; but it is to be hoped that the futile “cut and try” exploration will be indulged in less and less as time goes on and scientific principles of exploration are followed. The present problem is to decide what use to make of geophysical methods, in the light of present knowledge of the geology of the district. No very positive statements can be made in the following discussion of this subject. However, some experimental work has been done and considerable study has been given to the use of these methods by the geological department of the Calumet & Hecla Consolidated Copper Co., and we feel that we are in a position to say what there is to be said on the present status of geophysical methods as aids to geologic work in this district.

PRINCIPLES OF GEOPHYSICAL METHODS

All geophysical methods depend upon a contrast in the physical properties of the mineral deposit itself with those of the surrounding rock, or upon the discovery or delineation by means of such contrasts of some geologic feature to which mineral deposits are related. Thus, magnetic deposits are more magnetic, massive chalcopyrite deposits are better conductors, and salt domes have a smaller gravitative attraction than the surrounding rock. Or a mineral body which of itself may have no outstanding physical property amenable to investigation by geophysical methods may be related to certain geologic features which could be outlined by such methods. Thus, oil pools are discovered by outlining salt domes, hematite bodies by their relations to magnetic dikes, or chalcopyrite deposits by their relations to a certain contact. The essential condition in all geophysical work is that there be a detectable contrast in certain physical properties of the feature that is being sought, be it the mineral deposit itself or some geologic structure or condition to which the deposit is related. The physical property upon which the method depends may be magnetic polarity, magnetic permeability, electrical polarity or conductivity, density, elasticity, or one of certain other properties that are used more rarely. The manner and degree in which this essential condition of contrast in physical properties is met by the rocks and ore bodies of this district will be brought out in the following paragraphs.

THE THREE FUNDAMENTALLY DIFFERENT APPLICATIONS OF GEOPHYSICS

There are three radically different methods of conducting geophysical investigations. (1) If the physical properties of certain ore bodies or mineral deposits themselves have the necessary contrast with those of the country rock, that method can be selected which takes advantage of this contrast, and the work can be carried on with the direct object of locating the mineral deposits themselves. (2) It may be possible to take advantage of the physical properties of rocks associated with the mineral deposits, enabling structural features known to be related to the mineral deposits to be determined. (3) Geophysical methods may be used in general geologic mapping where the immediate objective is not so directly the location of mineral deposits as it is to build up a general geologic map which it is hoped will ultimately be of use in exploration. The following discussion will take up in order these three methods.

DIRECT APPLICATION OF GEOPHYSICS TO COPPER FINDING

EXISTING CONDITIONS

There are two general types of copper deposits in the Lake Superior district—the so-called lode deposits, which are in amygdaloid or more rarely in conglomerate, and the fissure deposits. The fissure deposits are unimportant as producers, having furnished less than 3 per cent of the copper of the district. A satisfactory geophysical method should be able to detect an amygdaloidal ore body having as little as 1 per cent of copper with as much as 30 feet of overburden, and it is therefore apparent at the start that the existing conditions are on the whole unfavorable. In the first place, the desirable degree of contrast between the ore bodies and the unmineralized lodes is not present. The sole difference, so far as we have been able to observe, between a mineralized lode and many unmineralized lodes is that the former has 1 per cent of its weight in native copper, which is $^{1}/_{300}$ of its volume, whereas the latter have less copper. Otherwise the mineralized lode is apparently the same in texture, mineralogy, porosity, permeability, water content, and chemical composition as dozens of unmineralized lodes, and for that matter many a lode is the same outside the boundaries of the ore shoot as it is within these boundaries, except for the small copper content.

The overburden of glacial drift, which covers almost the entire district, ranges from some hundreds of feet in thickness down to the vanishing point. Inasmuch as the prospecting in the last 80 years has involved a very thorough examination of the outcrops and the glacial drift, it follows that most of the undiscovered ore bodies are probably under rather deep overburden. There are probably none that crop out or are covered for any extent by less than 5 feet of overburden, and there are probably more covered by at least 20 feet of drift than by less than that amount. But with geophysical as with other methods applied on the surface, the thicker the overburden the less the chance of discovery.

The ore bodies are tabular and dip rather steeply, so that the outcrops, although of great length, are narrow, say from 10 to 20 feet on the average. The amygdaloid lodes are highly variable in width, some of them widening out from a few feet to 40 feet or more within a distance of 50 or 60 feet along the strike. These conditions reduce the chances of discovery by a geophysical method, because they introduce the possibility that the lines of observation may cross the lodes over the narrow spots. The conditions are very different from those in a district where the ore deposits are large, homogeneous, and equidimensional.

In most of the deposits the copper is very irregular in both size and distribution. Some of it is microscopic, being so fine that it gives a uniform pink tone to the including mineral, such as datolite or quartz. From these there are intermediate particles, nuggets, sheets, and masses weighing hundreds of pounds and even thousands of pounds. No physical continuity between the particles and masses exists to any degree, except possibly in the conglomerate ore, where the copper forms an interlacing cement in certain beds and is probably physically continuous over areas of some hundreds of square feet.

A very serious handicap to geophysical work in this district is the impossibility of making any exhaustive preliminary tests over known ore bodies. All such bodies have been worked from the surface downward, and very little “back” or unstoped ground was left at the surface. Furthermore, in most places there is a maze of power lines, pipe lines, tracks, and other artificial structures both on the surface and underground in the vicinity of the outcrops of the lodes, which would give much stronger “geophysical” effects than the modest copper content of the lodes themselves. In one or two places in the district it has been possible to make rather dubious tests over shaft pillars and old backs or roofs of ore bodies, but these have not been at all satisfactory nor convincing.

The conditions outlined above make it seem unlikely that geophysical methods can be of direct use in the exploration for copper deposits of the lode type. It is true that the fissure deposits present much more favorable conditions for geophysical work, but the history of the production of the district does not encourage the belief that fissure deposits of any great size could be found. Therefore exploration for fissures lacks the incentive that is offered by exploration for lodes.

The one outstanding feature that compels consideration of the possibilities of geophysics in this district is the fact that the ore mineral is native copper, which occupies a position in the series of natural electrical conductors far above that of the common sulphide minerals, such as chalcopyrite, which lend themselves so well to prospecting by electrical methods. It is possible that under certain conditions ore carrying 1 per cent of native copper would be as easily detected by electrical methods as ore carrying, say, 30 per cent of chalcopyrite. Because of the high conductivity of metallic copper, no such encouragement is offered to any other known method of geophysical exploration as there is to electrical methods. Of the other common methods the gravitometric and seismic have not been tried in lode exploration, simply because the conditions in the district seem to offer no hope for success. The possibilities of the use of magnetic methods in the search for copper deposits have been considered in conjunction with magnetic observations made for various purposes, and this work is described in succeeding paragraphs.

ELECTRICAL METHODS[63]

Direct conductivity and resistance methods.—Long before the development of the technique of the modern electrical prospecting methods, tests were made of the conductivity of the copper-bearing lodes. In 1893 Prof. James Fisher, now of the physics department of the

Michigan College of Mines, measured the resistance of stretches of copper-bearing lode in the Quincy mine and of the "Eastern" and Freda sandstones. Contact with the lode was made often by attaching the terminals to copper masses in the rock. The resistance was thus determined between points. About 1900 N. S. Osborne, at present with the United States Bureau of Standards, did some work along equipotential lines for the E. J. Longyear Co., both in the Lake Superior copper district and on the Mesabi iron range. Variable and apparently inconsistent measurements were obtained, and nothing of theoretical or practical importance resulted. Mr. F. N. Bosson, chief electrical engineer of the Calumet & Hecla Consolidated Copper Co., has found that it is possible in the deep salt-water zones in one of the mines to operate electric trolley locomotives without the regular metallic ground return, the conductivity of the water-soaked lode providing an adequate return circuit.

Spontaneous polarization.—The method of spontaneous polarization depends upon the electrical currents set up at the outcrop of an ore body because of its chemical alteration in the zone of oxidation. Observations were taken across the Isle Royale lode and across the Kearsarge amygdaloid and Kearsarge conglomerate lodes at Ahmeek by means of two movable electrodes, at a fixed distance apart, in contact with the ground. Traverses were made by shifting the electrodes along lines at right angles to the ore bodies. The potential difference between the electrodes was determined at the different stations by means of a potentiometer in circuit with the electrodes. Absolutely no electrical effects were observed other than those due to the ordinary weak and irregular ground currents. This test was by no means, however, a conclusive elimination of this method as of possible use in the district. The rate of oxidation of native copper, on which this method depends, is very slow compared with the rate of oxidation of sulphide minerals and would therefore offer less chances for the method here.

[63]We wish to acknowledge the assistance and cooperation of the experts in electrical prospecting who worked with us in what we regard as a piece of economic research. Without their technical skill and apparatus we could not have carried on the work. The experts who were in the district were Sherwin F. Kelly and Ingomar Tennberg with his assistant Mr. Roxtrom. In fairness to these gentlemen it should be stated that they regard the possibilities of their respective methods somewhat more optimistically than we state them in the following discussion.

Equipotential lines.—The method of equipotential lines depends upon the fact that if a direct current is sent through homogeneous ground between two electrodes the lines connecting the points having the same potential between and surrounding the electrodes are regular geometrical curves, of a character pre-determinable by the theoretical considerations involved. If, however, a body of rock or ore having either higher or lower conductivity lies within the field between the electrodes, the points of equal potential do not lie along the regular theoretical curves of the homogeneous field, but the lines are found to be distorted in the vicinity of the body of different conductivity. If it is of lower conductivity than the surrounding rock, the equipotential lines are crowded together near it. If it is of higher conductivity, as most ore bodies are, the equipotential lines are spread apart over it and in its immediate vicinity.

A brief test of this method was made over the Isle Royale lode at a point where it was assumed to be mineralized. Although the lode itself appears to have distorted the equipotential lines, similar distortions were made by adjacent amygdaloids not known to be mineralized. It is felt that both the theoretical considerations and these experiments throw doubt on the possibilities of the successful use of this method in its present stage of development in the Michigan copper district. It is apparently able to indicate the locations of amygdaloids and would therefore be of use in general mapping of structure and stratigraphy. However, magnetic methods are so much more quickly, simply, and economically used for the same purpose that there would be no excuse for using the electrical methods for general geologic work where magnetic methods apply.

Inductive methods.—In the inductive methods a loop of insulated wire is laid out on the ground, usually in a rectangular form. An alternating current provided by a generator or by an induction coil operated with a storage batery is sent through the loop. Thus a primary alternating magnetic field is set up within the loop of an ideal predeterminable shape if the ground is homogeneous. If a conductor such as an ore body of certain types is in the field, however, a secondary field is set up about the conductor. This secondary field is opposed to the primary field and therefore causes a distortion of the ideal primary field above and near the conductor. By ingenious methods of amplification and observation of the electromagnetic field within the loop, the secondary currents due to certain types of ore bodies can be recognized.

After some preliminary laboratory tests with specimens of rock and ore, the results of which were of an indifferent character, attempts were made to carry out practical investigations over known lodes. These included tests over the Kearsarge, Pewabic, and Baltic amygdaloids and the Calumet & Hecla conglomerate. All these trials showed the copper-bearing lodes to give weak though detectable effects. The strongest effects were shown over the Calumet & Hecla conglomerate and the Pewabic amygdaloid. After critical analysis, however, these tests were not as satisfactory as appeared at first sight. Dip-needle readings were taken along the same sections on which the electrical traverses were run. The Kearsarge and Pewabic amygdaloids and the Calumet & Hecla conglomerate showed varying degrees of magnetic disturbance in the vicinity of the lodes, and the electrical effects above the Kearsarge lode were definitely related to the magnetic anomalies rather than to the copper of the lode. The results of the tests at the Baltic and Champion mines, over the Baltic lode, were unsatisfactory for several reasons, among which were great thickness of overburden, exceptionally rough topography, wire fences, and the fact that where the conditions were most favorable and weak electrical effects were obtained over the lode similar effects were obtained away from the lode. The tests over the Pewabic lode, which may or may not be significant, indicated three mineralized lodes. It is possible that there are three mineralized lodes where the tests were made, inasmuch as mineralization in adjacent amygdaloids is a characteristic of the Pewabic ore body. Here again, however, there were complications due to magnetism of the traps and the possible presence of underground pipes, rails, wires, and cables. The conditions over the Pewabic lode were not such as to give a satisfactory test of this method.

The most satisfactory test was the one over the Calumet & Hecla conglomerate. Fortunately there was a shaft pillar 200 feet wide at No. 12 shaft, Calumet & Hecla. The shaft itself was not in operation, there being no shaft house nor machinery at the surface. The overburden is about 20 feet deep, the copper content of the rock is about 2 per cent, and the copper has the ramifying and connected form more common to conglomerate than to amygdaloid mineralization. The conditions for favorable results were the best to be expected in lode mineralization in this district. Furthermore, although the adjacent traps showed some magnetic disturbance, the effects were not strong nor sudden, the magnetic curves having long, gentle slopes. The results of the electrical tests, though weak, were the strongest obtained in the district and were apparently due to the copper in the lode.

These tests over known lodes indicated that under the most, favorable conditions of copper content, copper distribution, lack of complicating factors such as strong magnetism in the traps, and thinness of overburden the inductive method might detect an unknown copper-bearing lode. Furthermore, it was hoped that with additional work in the district the electrical prospecting experts might develop their methods to the greater degree of refinement necessary for search for the Michigan type of copper deposit. Accordingly, the electrical prospectors were engaged for further field work. Exploratory crosscuts at shallow depths were being driven at the time on the lands of the La Salle Copper Co. and the Cliff Mining Co. On the La Salle ground 7½ miles of double traverse was run, and on the Cliff ground 4 miles. The traverse lines were run at right angles to the strike and ranged in length from a few thousands of feet up to 3 miles. Two parallel lines of observation 200 feet apart were run in each test. This was thought to be safer than a single line of observation, because of the many variable conditions which might allow an ore shoot to give no effect in one spot but a detectable effect not far distant. Some of these lines were run over the ground to be explored by the crosscuts. Dip-needle readings were taken wherever electrical observations were made, and in many places electrical effects were obtained, only to be eliminated from further consideration by finding that they were due to the local magnetism of the rocks. This ability to eliminate electrical effects due to the magnetite in the rocks by a method so simple and economical is a decided advantage. In order to make doubly sure that certain electrical effects were actually due to magnetite, the testimony of the dip needle was checked by digging a 170-foot trench in one place where the electrical and dip-needle curves both showed disturbances. As was expected, no copper was found in the amygdaloids thus exposed. Certain electrical effects were apparently related to the water content of the overburden, weak disturbances being obtained where the traverse lines crossed from dry sand to wet swampy soil. No electrical indications were obtained which were suspected of being related to a copper deposit. However, no copper deposits were found in the crosscuts through a part of the territory covered by the electrical work.

Conclusions.—-The conditions existing in this district seem to be distinctly unfavorable to the successful application of geophysical methods to the direct search for copper deposits. The electrical methods would seem to have the best chance of success, and several of these have been given brief and inconclusive trials. The inductive method gave most encouragement. The present situation may be summarized as follows:

1. Low-grade deposits, erratic distribution of copper, erratic variations in thickness of the lodes, which on the average are thin, lack of contrast between conductivity of the mineralized and the unmineralized rock, thick and irregular overburden, the chances that the greater number of undiscovered lodes are in the regions of thicker overburden, the interference of magnetite in the traps, and the high water content of the permeable amygdaloids, unmineralized as well as mineralized, are all features that tend to make electrical prospecting difficult.

2. There are practically no places in the district where conclusive tests of geophysical methods can be made over known ore bodies.

3. Present electrical methods were developed chiefly to explore for massive sulphide deposits, which apparently give very much stronger and more definite results than the disseminated native copper deposits. Much greater refinement in technique seems to be necessary before these methods can be used with confidence in this district.

4. Those who are expert in these methods feel that they have passed the experimental stage, and this feeling is doubtless justified as regards massive sulphide deposits; but considerably more experimenting must be done before these methods can be applied in the Michigan copper country with the same degree of confidence. It is felt that there is enough of a chance of successful adaptation of these methods to the conditions of the district to warrant further research. The research should be carried on by men who are not interested in the commercialization of any particular method, and it should be financed as experimental work rather than as a method which has been demonstrated to be successful with ore bodies of this type. A Federal

Government or State organization could undoubtedly handle the experimental work. At any rate, as experience is gained in the practice of the methods elsewhere, the tendency will undoubtedly be to become more and more expert in the detection and interpretation of the weaker effects due to lean disseminated deposits, thus approaching a solution of the problem of this district.

5. Because of the weakness of the electrical effects which these copper deposits produce, other weak effects due to such features as topographic roughness, small quantities of magnetite, and irregularities in groundwater distribution, which are in districts of massive sulphide deposits of a small order of magnitude compared with the electrical effects of the ore body, become in the Michigan district of about the same order of magnitude as the effects due to the copper and therefore lead to confusion.

6. Too great a coincidence of favorable conditions seems to be required for positive results. The most satisfactory of the tests over known lodes was that over the Calumet & Hecla conglomerate, where the copper content was exceptionally high, the copper distribution exceptionally favorable, and the overburden probably rather less than the average of that covering undiscovered deposits.

7. If it is true that such a coincidence of several favorable factors is required for a deposit to give a positive effect where the line of observation happens to cross it, then negative results do not go very far in condemning the ground explored by electrical methods.

8. The encouraging features are that the ore mined is native copper; that despite the fact that the methods have not been developed for the purpose of detecting such weak effects, trials over known ore where conditions are most favorable give detectable though minute effects; and that the dip needle offers a rapid, inexpensive, and simple means of eliminating one of the causes of uncertainty in the interpretation of electrical effects.

No attempt has been made in this discussion to present the technical side of geophysical prospecting. Some of the more important papers on the subject in the English language are listed in an article by Hans Lundberg.[64]

INDIRECT APPLICATION OF GEOPHYSICS TO COPPER FINDING

If there were surrounding the copper deposits a widespread zone of alteration characterized by excessive development of magnetite or the destruction of the magnetite already present in the traps, or if the copper deposits were related to certain structural features such as folds, fissures, faults, unconformities, or contacts, geophysical methods that could detect such features would be of indirect use in the search for the deposits. The copper-bearing series is by no means homogeneous magnetically. Different flows and different parts of the same flow vary in magnetite content. Furthermore, there are erratic concentrations of magnetite all over the district, some of them in the bedrock, others in glacial boulders. It would therefore be expected that irregularities in compass or dip-needle readings would be obtained somewhere in the vicinity of the copper deposits as well as elsewhere. Such erratic readings near the copper deposits naturally attracted attention, and it has even been asserted that “There is certainly a deflection in the vicinity of the richer copper belts.”[65] Work thus far accomplished, however, indicates that the magnetic deflections in the vicinity of the copper deposits are simply those due to the primary magnetite concentration in the original rocks, unchanged by subsequent mineralization, and therefore in no way related to the copper deposits. Similarly, no structural relations, such as those suggested above, are known to exist. Some ore bodies are on synclinal and some on anticlinal cross folds; others occur where the strike is essentially a straight line for miles. Some have thousands of cross faults, strike faults, and fissures; others have practically none. Therefore, existing knowledge indicates that there is no present possibility of applying geophysics in this indirect manner. So far as now known, the only such application of geophysics likely to be feasible would be to determine the lateral extensions of a new deposit by tracing the strike of the lode in which it lies with the dip needle or by some similar means.

[64]Practical points on electrical prospecting for location of mineral deposits: Min. Cong. Jour., vol. 12, pp. 737-738, October, 1926.

[65]Meuche, A. H., The development of the copper mines of Lake Superior and their geological relations: Michigan Geol, Survey Pub. 6 (Geol. ser. 4), vol. 2, pp. 887-931, 1911.

APPLICATION OF GEOPHYSICAL METHODS TO GEOLOGIC MAPPING

EARLY GEOLOGIC WORK

Very early in the history of the district fair geologic maps were made by following trap and conglomerate ridges, thus making general correlations of beds at certain horizons and determining the general structure. Thus it was a simple matter, for instance, to trace the Greenstone for many miles in Keweenaw County and the Evergreen flow in Ontonagon County because of the almost continuous outcrops along prominent bluffs. As one after another of the lode deposits were discovered, the idea that these few “master lodes” extend throughout the district took hold, and it persists to the present day. The great object of the explorers was to locate these “master lodes”—the Isle Royale, the Pewabic, the Calumet & Hecla conglomerate, and the others—on their particular properties. This was a matter of stratigraphic mapping, and therefore infinite pains were taken to ascertain the stratigraphic relation of these beds to the more easily traceable key beds. Thus there followed a period of trenching based upon accurate surveying, in the attempt to follow from one end of the district to the other the lodes that were known to be mineralized at some point. The introduction of the diamond drill opened up great possibilities in the determination of stratigraphy, and extensive campaigns of drilling followed. It would be safe to estimate that a million feet of diamond drilling has been done in the district, a large share of it being chargeable to purely stratigraphic purposes, because few of the explorers were satisfied with the diamond-drill core as evidence of the presence or nonpresence of commercial deposits. The net result of all this drilling was a very detailed knowledge of the stratigraphy but no discovery of new ore bodies, with the possible exception of the Lake lode, which produced about 7,000,000 pounds of copper before it was forced to shut down.

While all this drilling, surveying, trenching, and shaft sinking was going on in search of the "master lodes" in the copper district, magnetic instruments were being used just a few miles to the south, in the iron districts, not only in locating iron deposits but in tracing horizons of magnetic beds. Magnetism in the rocks of the copper district was noted on the plats of the original land survey, and in 1873 Brooks published an account of the use of magnetic observations in the Michigan iron districts.[66]

It is certain that the same knowledge of the structure and stratigraphy of the district could have been obtained much more economically had the dip needle been used in conjunction with the other methods, or, to put it another way, the same amount of money would have furnished much more structural and stratigraphic information had the dip needle been used in each locality before trenching, drilling, or shaft sinking. Many of the holes and shafts would never have been put down, and those that were sunk would have been more accurately located and directed. The present problem, however, is concerned with what should be done in the way of mapping geology by applied geophysics now and in the near future.

[66]Brooks, T. B., Michigan Geol. Survey, pt. 1, vol. 1, pp. 205-243, 1873.

IDEAL CONDITIONS FOR MAGNETIC WORK

Magnetic contrasts in rocks.—Although gravitative, seismic, and electrical methods would undoubtedly serve to determine the geologic structure, the conditions for mapping by means of magnetic observations are so much more favorable that the other methods are not to be considered. The interbedded flows and conglomerates, many of them extending along the strike for tens of miles, carry magnetite in varying quantities. Thus there are the contrasts in adjacent rock bodies which form the indispensable conditions for any successful geophysical work. The variation in the magnetite content of adjacent beds causes distortions in the earth's magnetic field, and there are several types of instruments which can detect these distortions.

Simplicity of geologic structure.—The fact that the magnetite content and concentration is a property of many beds in which it occurs and that as a rule wherever one of these beds is crossed it can be depended upon to give a magnetic effect peculiar to itself makes it possible to trace certain beds for miles by the simple observation of this effect. Furthermore, the beds are parallel to a remarkable degree, so that once a positive correlation is established rather vague features in the near-by parts of the section, if they conform with the established correlation, can be related to other features at definite horizons with much more certainty than would be possible where the structure is more complex. These conditions make the interpretation of most of the magnetic data very simple.

Numerous geologic checks available.—One who undertakes to do magnetic work of the general reconnaissance type, crossing the mineral belt at regular intervals, should not, over the greater part of the district at least, be at a loss to know where he is geologically. It is possible in most places to tie in to known geologic features, because of the many diamond-drill sections and the extensive explorations. The question immediately arises why, if the geology is so well known, should any extensive magnetic mapping be undertaken? This is indeed a debatable question, and it will be considered throughout this discussion. The point to be made here is that if it should be decided to carry on any magnetic surveying, the existing knowledge of the district is sufficient to enable a close coordination between magnetic effects and known geology to be maintained during the work.

Favorable geographic and topographic conditions.—The country is very well adapted to the rapid methods of magnetic surveying. The copper-bearing formation as a whole occupies a long, narrow belt, in which the longer dimension is parallel to the strike. Roads and railroads extending along the belt within the limits of the series provide easy access to the belt almost from end to end. Over the greater part of the district a complete dip-needle traverse of the formation can be laid out at any place and completed with a few days. Numerous section corners, roads, diamond-drill holes, and mine shafts, abandoned and operating, provide convenient geographic tie points. United States Geological Survey topographic maps covering that portion of the district extending from Cliff to Globe are available.

THEORY AND PRACTICE OF MAGNETIC SURVEYING

Fundamental principles.—Over areas underlain by magnetically homogeneous rock material the earth's magnetic field is essentially uniform, the lines of magnetic force having a uniform inclination and spacing; or, expressed in another way, the magnetic field is uniform in direction and intensity. If a rock formation of different magnetic permeability lies within the otherwise magnetically homogeneous rock formations, the ideal or normal earth's field is distorted in the vicinity of the magnetically different formation. The lines of force are steepened or flattened and they are crowded together in some places and spread out in others; or, to put it more properly, there are local variations in the direction and intensity of the earth's field. Mapping geology by means of magnetic instruments, herein referred to as "magnetic surveying," simply involves the detection, tracing, and geologic interpretation of these local variations or anomalies in the earth's magnetic field.

Instruments.—A variety of instruments have been designed for this purpose. Sighting on a distant object and walking directly toward it, taking the magnetic bearing of the line traversed at intervals with an ordinary compass, may serve to detect variations in the direction of the horizontal component of the earth's field. Compasses equipped with sundials are used to determine the true meridian at a given station, and the deviation of the horizontal component of the earth's field, or the declination, is observed by reading the angle between the meridian and the position of the compass needle. The period of vibration of the needle from place to place can be determined, and a measure of the variations in the horizontal intensity of the earth's field thereby obtained.

The most useful all-round instrument for magnetic surveying, in its simplicity, easy repair and adjustment, lightness in weight, sensitiveness, rapidity in taking observations, and satisfactory results, is the dip needle. Essentially it is a magnetized needle which swings in a vertical plane about a horizontal axis. Instead of swinging about its center of gravity, like the dip needles used in the study of terrestrial magnetism, it has a counterweight which is so adjusted that the needle assumes a position most sensitive to magnetic variations of the normal field. Thus in the Lake Superior district the needles are adjusted to come to rest in a nearly horizontal position in the normal field. In making an observation, the magnetic meridian is first determined by using the dip needle in the horizontal position, as with an ordinary compass. It is then tilted up into a vertical plane of the meridian and leveled by means of a leveling bubble, and the deflection of the needle from the horizontal is read in degrees. By standardizing this procedure, which is almost essential if readings that will be truly comparable are to be obtained, it is possible to make and record a dip-needle observation in 30 seconds.

More complicated and more sensitive instruments for making magnetic observations are available. There are, for instance, various types of magnetometers which determine all the elements of direction and intensity. The additional delicacy and refinement of the results yielded by such instruments in ordinary work, however, do not compensate for the clumsiness, need of transit surveys for locations of observation stations, liability to damage, difficulty in repairing, and time consumed in preparing for and making observations.

Plotting of results.—There are several methods of plotting dip-needle readings. A magnetic contour map may be made by connecting points which give the same dip-needle variations. Another method is to lay out the line of traverse on the map and plot a profile of the dip-needle readings from it as a base. This is the method used in showing the magnetic data on the accompanying map (pls. 6-9). The straight line represents the line of traverse, which may be either a transit line or a road. From it as a base the dip-needle readings in degrees are plotted. Where the north end of the needle is below the horizontal, the reading is plus, and the point is plotted at a distance above the traverse line proportionate to the number of degrees of deflection. Where the south end of the needle is below the horizontal the reading is minus, and the point is plotted below the traverse line. Where several men with different dip needles have taken observations in the same area, it is desirable to reduce all the observations to a common basis in order that they may be satisfactorily compared. In order to do this the needles are all read at a single station, preferably one where the earth's field is normal, and thus for each instrument a "normal" reading is obtained, and in plotting on the map all the readings in degrees above and below the horizontal are recalculated to degrees above and below the "normal." This has not been done in the profiles on the accompanying map, because the readings were all taken with one instrument, so adjusted that the "normal" position of the needle was about horizontal, or approximately 0°. The curves are so plotted that they are correctly read by one facing north or east.

HISTORY OF WORK IN THE LAKE SUPERIOR KEWEENAWAN ROCKS

Early observations.—The earliest records of the observation of magnetic variations are those made at the time of the original land surveys. Some of these are noted on the township plats. While the land survey was still in progress geologic work by Jackson and his assistants was being carried on, and some attempt was made to find out whether there was any relation between the copper deposits and the magnetic anomalies.[67] This work was not brought to a stage where any definite results one way or another could be announced.

Recent work.—During the many years in which systematic magnetic surveying has been carried on in the iron districts occasional traverses were made, intentionally or unintentionally, in areas underlain by Keweenawan traps. Magnetic lines of attraction, supposedly due to iron-bearing formation, after investigation by diamond drilling or otherwise have been found to be related to lava flows.

In recent years the State geological surveys of Minnesota and Wisconsin have conducted systematic investigations of the Keweenawan igneous rocks, using magnetic observations as one of the means of mapping the geology. So far neither organization has published a formal report of the work, although brief preliminary papers have been written presenting some of the results.[68] The magnetic work in the Minnesota Keweenawan was done largely in the area of the great Keweenawan intrusive, the Duluth gabbro. Enough work was done over the traps to the south of the gabbro to show strong magnetic attraction at certain horizons in those beds. In more recent years the Minnesota Geological Survey has done some magnetic work in the Keweenawan lavas, but it was more or less incidental to other projects and has not been made the object of serious investigation.

[67]Jackson, C. T., Report on the geological and mineralogical survey of the mineral lands of the United States in the State of Michigan: 31st Cong., 1st sess., S. Ex. Doe. 1, pt. 3, and H. Ex. Doc. 5, pt. 3, pp. 586-605, 1849.

[68]Broderick, T. M., The relation of the titaniferous magnetite of northeastern Minnesota to the Duluth gabbro: Econ. Geology, vol. 12, pp. 663-696, 1917; Some features of magnetic surveys of the magnetite deposits of the Duluth gabbro: Idem, vol. 13, pp. 35-49, 1918. Aldrich, H. R., Magnetic surveying on the copper-bearing rocks of Wisconsin: Idem, vol. 18, pp. 562-574, 1923.

By far the most comprehensive magnetic surveying in the Keweenawan has been done by field parties of the Wisconsin Geological and Natural History Survey under the immediate supervision of H. R. Aldrich. This work was started by W. O. Hotchkiss, at that time Director of the Survey, in 1922, and has been carried on by Mr. Aldrich from the beginning to the present time. Many hundreds of square miles of drift-covered Keweenawan rocks are being mapped structurally and stratigraphically by magnetic methods. The scattered outcrops are thus placed in their true relation to one another, and faults, folds, formation boundaries, unconformities, and individual beds are being mapped largely by magnetic methods. A few diamond-drill sections are available, and these, together with some good exposures of the section along streams, enable the observers to tie in the magnetic features to the geology from place to place. Except perhaps the land-classification work over possible iron-bearing lands, done by the same organization,[69] this is, so far as we are aware, the most comprehensive magnetic survey ever made with no immediate application to ore finding as a direct objective. However, there are no known theoretical grounds which in any way discourage the idea that the possibilities of valuable copper deposits existing in Wisconsin are not as good as in Michigan, and the fact that they have been found in Michigan and not in Wisconsin is not conclusive. The members of the Wisconsin Geological Survey believe that

> The areas away from Keweenaw Point may perhaps at once come in for new examination, but we feel that if not at present the attention will come within a very few years. * * * Then the question comes, if the exposures are so meager and if the drift cover is so deep that geologists in the past have not been able to obtain the data necessary for a final conclusive opinion, what can a geologist do in such an area? So far as a thorough examination and testing of the rock is concerned, we of the survey fully agree that ordinary methods hold out little hope for an immediate solution of the problem. But we believe that there is much that may be done on the surface by means of a magnetic survey that will aid campaigns for the systematic disclosure of what lies below the drift.[70]

Besides this magnetic work on the Keweenawan formations outside of the Michigan copper district, magnetic observations have been made in recent years within the district itself, the results of which are discussed below.

[69]Hotchkiss, W. O., and others, Mineral land classification showing indications of iron formation: Wisconsin Geol. Survey Bull. 44, 1915.

[70]Aldrich, op. cit., p. 574.

RECENT WORK WITHIN THE COPPER DISTRICT

We have no knowledge of any attempts at systematic magnetic work in the Michigan copper district between that at the time of Jackson and the present work by the geological department of the Calumet & Hecla Consolidated Copper Co. This department has carried on some magnetic work at three different periods, with as many different purposes in view. The purposes and general results of the work in these periods are briefly as follows:

Work prior to 1925.—When the special geologic survey of the Calumet & Hecla Mining Co. was started on the ground in 1920, it was necessary to make tentative decisions as to the lines of research to be taken up first. The statements found in the literature that copper-bearing lodes caused magnetic disturbances were of course a challenge, and some observations were made with the dip needle in 1920 to check this statement. As a result of these observations and those made at a later date for the same purpose, it was decided that there were no obvious magnetic peculiarities in the vicinity of the copper deposits which could be detected by ordinary dip-needle practice in the light of present knowledge. Magnetic traverses have been run across the Calumet & Hecla conglomerate and the Kearsarge, Pewabic, and Baltic amygdaloid ore bodies. On the other hand, we do not presume to state positively that a campaign of magnetic work carried out over a period of perhaps several years by competent geologists would not reveal’magnetic peculiarities by which ore bodies might be detected. Our present position is just as it was after the tests in 1920—that there are more promising lines of research, which therefore demand first attention. The brief magnetic work of the first summer likewise demonstrated the possibility of tracing the strike of certain beds by their magnetic characteristics.

Work in 1925.—The magnetic work done in 1925 was intended for the specific purpose of eliminating effects that were due to magnetite of the traps and sediments from further consideration in the study of’ the results of electrical prospecting. The locations of the magnetic traverses thus were coincident with those of the electrical traverses. Eight sections, with a. total length of 15 miles, were made on the lands of the La Salle Copper Co., and two sections, with a total length of 8 miles, on the lands of the Cliff Mining Co. All this work was in what may be termed the productive mineral belt. Magnetic observations were taken at all the stations where electrical observations were made. These were spaced 30 feet apart along surveyed lines at right angles to the strike. The magnetic traverses at La Salle are shown as dip-needle profiles on Plate 8. Those at Cliff, made in connection with electrical prospecting, are the straight-line traverses shown on Plate 7. The results of this dip-needle work in eliminating electrical effects due to the magnetite of the rocks were most satisfactory. The observations made at this time also furnish data of use in the study of the possibilities of magnetic work in structural and stratigraphic geology.

Work in 1926.—As a preliminary to exploratory work about to be started in Keweenaw County, it was decided for various reasons to carry on some magnetic work in 1926. At this time 38 miles of traverses were run, and magnetic observations were made at 25-foot intervals. This work was done in the autumn, and as it was desirable to get as many data as possible before winter stopped the work, it was decided to take the observations along the several roads crossing the formation, carrying locations by pacing and Brunton compass. The numerous possible tie-ins to well-located features, both geographic and geologic, made this a satisfactory method, although, of course, the plotting of results was more difficult than it would have been if section lines had been followed. The data so obtained, added to those of previous years, form the basis of the following discussion of the application of magnetic methods to structural and stratigraphic mapping in this district. We have made a total of over 60 miles of traverse and over 12,000 observations. These figures are by no means impressive when compared with similar figures of the larger State surveys or those of many iron companies. They become impressive, however, when it is realized how high a proportion of them can be tied up closely to the local stratigraphy because of the numerous diamond-drill explorations and outcrops.

RESULTS

Determination of strike.—One of the simplest and most easily obtainable deductions by means of magnetic work is the local strike. A magnetic bed is picked up and crossed at suitable intervals, and the line connecting that particular feature from section to section is the strike of the bed. It is desirable to know the strike in diamond drilling and in sinking inclined shafts. Examples of diamond-drill holes that would have been pointed differently and would have yielded more satisfactory information may be seen on the map showing the Cliff Mining Co.'s lands. Examples of shafts that would have been sunk differently had the strike been known are the Lake No. 1 and the New Baltic shaft, near the Keweenaw fault. Numerous examples of strike lines determined magnetically may be seen by reference to the magnetic sections on the maps. Those on the La Salle lands are especially good.

Tracing beds at specific horizons.—In earlier days, when certain lodes were known to be mineralized in different places, it was desirable to find the lateral extensions of the ore bodies, not only on the properties where development was going en but on adjacent properties. This work involved first tracing the strike of the lode itself, by trenching, surveying, diamond drilling, pit or shaft sinking, and crosscutting or by a combination of these methods. In many places the desired information could have been obtained at an insignificant fraction of the expense and time by dip-needle work. Such a problem would be solved by getting the horizontal distance from the lode to one or more near-by magnetic beds, tracing these beds with the dip needle onto the adjacent lands, and then measuring back to the position of the lode. Every engineer who has worked in the district can cite instances where time and money could have been saved had the location of some particular lode been known to the explorers. There are parts of the section where magnetic work of this type would be less successful than in other parts. For instance, the magnetic deviations are much weaker in some places toward the Keweenaw fault than higher in the section. Not enough magnetic data are available to reveal whether this is a secondary characteristic of all rocks near the fault or a primary characteristic of that part of the section. At any rate, it would be much more difficult to trace lodes by dip-needle deviations of only 1° or 2° than it would by deviations of 6° or 7°.

Location of faults, folds, and fissures.—Folds in the formation can be easily determined by magnetic methods, the magnetic lines following the curvature of the bedding. Similarly faults can be located by offsets in the magnetic lines, although in some localities the magnetic lines do not extend right up to the fault plane, which probably means that the magnetite has been altered in the zones of crushing adjacent to the faults. This apparent destruction of magnetite near faults suggests the possibility of locating fissures to be explored for copper deposits. Magnetic methods would probably have been of great aid in solving the structural problems where there are local complications, especially near the Keweenaw fault. Such areas are present at the Mayflower-Old Colony, New Arcadian, Lake, and elsewhere. The possibility that these areas are too close to the Keweenaw fault to yield traceable lines of magnetic attraction would make magnetic work of no avail, but so far as we are aware magnetic methods have not been tried in any of these places, and the explorers have had to feel their way along by means of expensive diamond drilling and underground work.

Other relations of magnetic features to geologic features.—The dip-needle profiles on the accompanying maps show certain recurring features, the recognition of which is of importance because they are the bases of correlation from one section to another. There are long stretches where the curve is essentially flat and without character; other stretches where the curve is rough, due to closely spaced areas of high, low, and normal attraction; other stretches where the curve is a broad sag or an arch; and still others where the curve, though rough in detail, is in a broad way a succession of sharp rises, falling back to normal more gradually. The latter feature Aldrich[71] likens to the teeth of a ripsaw. These peculiarities are the resultants of several factors, of which some are related to primary features of the rocks and others are not. The underlying cause of the variations in the magnetic field at the present surface is the unequal primary distribution of magnetite in the inclined succession of traps and sediments. To some extent this unequal distribution is related to differences in the magnetite content of successive flows. There are several types of extrusive rocks, varying chemically, mineralogically, and texturally. They range in composition from rather acidic felsites to the more basic members of the basalt group, and they vary widely in their magnetite content. Unequal distribution of magnetite is also the result of the unequal thickness of the flows. In general, the thicker flows give the stronger magnetic effects, probably in part because the slower cooling of the thick flows allows a more complete segregation of the magnetite to occur, and therefore a flow, say, 200 feet thick would have a greater magnetite concentration than five 40-foot flows of the same composition as the 200-foot flow. In general, the thicker ophites seem to cause the stronger magnetic effects. The La Salle profiles show this feature, the irregular curve from the neighborhood of the Calumet & Hecla conglomerate to the Kearsarge conglomerate being due to a series of rather thick ophites. On the other hand, the more acidic glomeroporphyrites between the "Mesnard bed" and No. 17 conglomerate do not give much magnetic variation, nor do the thin feldspathic melaphyres and ophites just above and below the Kearsarge amygdaloid.

[71]Aldrich, H. R., op. cit., p. 566.

Local alterations, none of them so far recognized as being related to copper mineralization, have destroyed some of the primary magnetite so that its present distribution is probably more erratic than it was originally. The most notable of these alterations is the one which oxidized the ferrous iron of each flow while it was still hot, starting, perhaps, as soon as the flow reached the surface and continuing throughout the period of crystallization and even later. Thus there is very little magnetite left in the amygdaloidal tops of the flows, and the crystals of magnetite and other ferrous iron minerals deep within the flows are replaced to varying degrees by hematite. Even more erratic is the alteration of the magnetite in the vicinity of the faults and fissures. Little is known about this alteration at present, but there are strong indications that it exists. For instance, the traverses which crossed the thick Greenstone flow in Keweenaw County along the roads through the big gaps caused by fissure zones show flat magnetic curves, whereas those that crossed at the Ojibway and North American, away from any known fault or fissure zones, show violent magnetic effects in the Greenstone area.

Finally, there is the masking effect of the overburden and to some extent of the topography. In general, the thinner the overburden the more ragged the dip-needle curve, the effect of the overburden being to smooth out and generalize the curve, eliminating some of the minor variations and combining series of closely spaced magnetic highs and lows into broad areas of normal deflections or of uplift or depression. What is taken to be an effect of thick over burden is displayed by the northern part of the traverse running from Lac La Belle to Mandan. In the lower part of the section, just north of the point where it diverges from the section extending northwestward toward Delaware, the curve is rough and the overburden is thin, with many outcrops. Numerous correlations on the basis of magnetic observations can be made between the two profiles in their southern parts, but in their northern parts the two sections are very different. The western one, through the Delaware area, shows the magnetic characteristics of that part of the section as displayed in profiles run across it elsewhere. The eastern one, through the Mandan area, is much more smooth, and in parts of the section where the rocks in most places cause great magnetic contrasts the resultant curve is without marked characteristics. The sharp, strong magnetic effects especially characteristic of the thick ophites in the vicinity of the Calumet & Hecla conglomerate are entirely lacking in the Mandan profile. Diamond-drill holes in both of these areas show that at Delaware the drift is much thinner than at Mandan, and it is thought that the thicker drift at Mandan is largely responsible for the lack of the usual strong magnetic contrasts in that section.

Abrupt changes in topography modify the magnetic curves to some degree, and the varying thickness of drift, together with abrupt topographic changes, may tend to make the correlation of geologic horizons with their related magnetic effects somewhat difficult.

Persistence of magnetic features.—-The value of magnetic work in mapping stratigraphy is dependent upon the persistency of the magnetic properties of the beds at different horizons, which is pictured by a similarity in the dip-needle curves for different sections across the strike. If the concentrations of magnetite were haphazard and not characteristic of any particular geologic horizons, the magnetic lines would not be parallel to the strike or to any other feature, and therefore the magnetic observations would be of no use in geologic mapping. Such is not the case. The magnetite concentrations are characteristic of certain geologic horizons. Some of them are much more persistent than others, however, like the flows themselves. Some magnetic effects can be followed for many miles; other effects are difficult to find in a parallel section but a few hundred feet distant. The magnetic attraction at about the horizon of the Ashbed lode is well marked in five out of the six sections that cross it in Keweenaw County. It is also present many miles to the south, in the La Salle area. This is an example of a very persistent and reliable magnetic line. Another persistent magnetic line is found about 1,300 feet horizontally above the Ashbed lode in Keweenaw County. In general, the closer the traverses the greater the number of possible magnetic correlations. The double traverse lines 200 feet apart in the La Salle area show in most places practically parallel magnetic curves, and correlations between them can be drawn at 100-foot intervals or in places even less. The distance between pairs is about half a mile, and the number of possible correlations between pairs is much less than that between the two curves making each pair. In Keweenaw County, where the distance between traverses is still greater, the number of reasonable magnetic correlations is correspondingly less. The experience in correlating between diamond-drill sections is the same.

Inspection of the maps shows that where the drill sections are close together many more correlations can be made from hole to hole than where they are widely spaced. The flows thin out and disappear, and as a result the corresponding magnetic lines become weaker and disappear. Where one flow wedges out and is replaced along the strike by another flow, the two are generally of the same petrographic type. For instance, where one of the more basic flows, such as an ophite, wedges out, its place along the strike is not assumed by one of the more acidic flows, such as a glomeroporphyrite, but commonly by another ophite or a flow of similar composition. This means that the flows poured out during the same stages of the igneous activity were of a similar character. Thus there are portions of the section characterized by glomeroporphyrites, others characterized by ophites, and still others by intermediate types. The changes from a part of the section characterized by one rock type to a part characterized by another rock type are not abrupt, for there are in most places several flows of an intermediate type between the two extremes. Thus between a group of ophites and a group of feldspathic melaphyres there are likely to be a few feldspathic ophites and some feldspathic melaphyres with a faintly developed ophitic texture. Most of the accompanying maps and sections show this grouping of the various types of flows, and it is discussed elsewhere. The point to be considered here is to what extent this persistence of the belts of flows, in spite of the lack of persistence of the individual flows within the belts, is reflected in the magnetic profiles. An inspection of the magnetic profiles shows that the belt of glomeroporphyrites between the top of the Greenstone (or the base of the "Mesnard bed") and the Ashbed lode (or the overlying No. 17 conglomerate) is relatively homogeneous magnetically but that the ophites between the Calumet & Hecla and Kearsarge conglomerates are not magnetically homogeneous as a belt. This difference causes smooth curves in the one case and rough curves in the other. Other belts have their characteristic magnetic effects. In general the persistence of magnetic effects bears a close relation to the persistence of the beds which cause them. A given magnetic line probably weakens and disappears as the flow which causes it thins and wedges out. A broad general feature of the magnetic profiles related to a group of flows of a given type is more persistent, just as the group is more persistent than the individual flows of which it consists. Aldrich[72] inferred this wedging out of individual flows and the existence and persistence of the belts of flows of similar composition in the Wisconsin Keweenawan almost solely from the details and broad features of his magnetic profiles.

Magnetic correlations.—-The foregoing discussion will enable the reader to appreciate the many variable conditions which must be taken into account in the interpretation of magnetic observations in terms of stratigraphy and structure. The first step in this interpretation is to correlate the magnetic features of two or more adjacent cross traverses. The next step is to correlate the magnetic features with the local geology—to tie up certain magnetic lines with the formations which cause them, and to relate broad magnetic features to similarly broad geologic features. Finally, by working from areas where the geology is well known to areas where the geology is less certain, the determination of the geology from the magnetic features becomes possible. Some interpretations of these features are indicated on the maps. The most reliable magnetic correlations from section to section are shown. These are more numerous in the more closely spaced traverses. Other possible correlations are apparent, but most of these have not been indicated because they are less certain. Further data would of course allow more accurate interpretations to be made. It is thought that even the few traverses that are at present available are worth presenting, as they serve to show the possibilities of the method in a district where they form a simple, rapid, and economical means of obtaining valuable geologic information.

PRESENT ATTITUDE TOWARD MAGNETIC SURVEYING

As a result of this study of the application of magnetic methods to geologic problems in this district the conclusions set forth below have been reached. These conclusions are, of course, not to be regarded as final. Further data will undoubtedly strengthen or modify them or set up some others in their places, if any of them should prove to be unsound.

1. There is no reason to hope that the copper ore bodies in amygdaloids and conglomerates can be detected by magnetic methods. No feature of magnetite distribution is known to be in any way related to the presence of the copper. There may be zones of alteration adjacent to fissures and faults, in which some of the magnetite has been destroyed. Some of these zones may be mineralized, and it is conceivable that a search for fissure deposits in drift-covered country might be aided by magnetic surveying.

[72]Aldrich, H. R., op. cit., p. 568.

2. Magnetic methods are of use in the preliminary stages of the exploration of specific areas. Dip-needle traverses across the formation at closely spaced intervals give a great amount of detailed information concerning the geology, such as the strike, the presence of faults with amount of offset, a general idea of the thickness and character of the traps, and some idea of the thickness of overburden. For this purpose the traverses should be made at intervals of not more than a quarter of a mile, and they should be even more closely spaced where any structural complications are found. Readings should be taken at about 25-foot intervals along the traverses.

3. Where it is desirable to trace the strike of a specific lode, magnetic methods will ordinarily serve. A traverse should be run across the formations where the position of the lode is known, thus determining its relation to the near-by magnetic beds. Then parallel traverses are made at intervals into the area where the position of the lode is to be traced, the lode being located by its determined position with respect to the magnetic beds.

4. Magnetic methods should help in solving local structural problems such as those pertaining to faulting or to pitching synclines and anticlines like those that occur at the Lake and New Arcadian mines.

5. Since the beginning of geologic work in the district emphasis has been placed upon detailed stratigraphy. As a result the stratigraphy is especially well known. Individual conglomerates and traps have been traced for more than 50 miles along the strike. The character of the beds in the different parts of the section is known from one end of the district to the other. All this detailed information has been obtained by surface mapping, diamond drilling, and underground openings. There are some places in the district, of course, where the structure and stratigraphy are not so well known as in other places. Such areas occur south of Victoria and east of Mandan, and the next step in stratigraphic and structural mapping in the district might well be accomplished by a magnetic survey of these areas. Anyone who would enter into such a project should be convinced of its justification on the basis of its scientific or economic importance. It would be of considerable scientific interest to map the geology from the Victoria mine to the Wisconsin line, thus connecting in greater detail the geology of the copper district with that of the Wisconsin Keweenawan, now being mapped by the Wisconsin Geological Survey. Such a project would be especially valuable to the State of Wisconsin, because it would enable an interpretation of the Wisconsin geology to be made more closely in terms of the geology of the copper-producing portions of the Keweenawan series.

One of the most interesting studies yet to be made in the Michigan Keweenawan is along the southern and eastern edges of the “Eastern” sandstone. The so-called South Range branches off from the main Keweenawan belt in the vicinity of Bessemer and Wakefield and extends southeastward for over 50 miles. It consists of northward-dipping Keweenawan traps and sediments, overlain by the “Eastern” sandstone. Also within the sandstone area are scattered outcrops of trap, as at Silver Mountain and in the Sturgeon River valley. A thorough study of the stratigraphy, petrography, and structural relations in this area would undoubtedly throw some light on the relations of the “Eastern” and “Western” sandstones and of the traps and the “Eastern” sandstone, and on some of the little understood features of the Keweenaw fault problem, such as amount of movement, thickness of sandstone, and rocks that underlie the sandstone. We have more than once heard practical men in the district seriously raise a question as to the economic possibilities of the Keweenawan formation southeast of the Keweenaw fault, beneath the “Eastern” sandstone. It is our opinion that a study of the South Range and the sandstone area to the north and east of it offers an almost certain chance of making important scientific contributions to some of the fundamental structural problems of the district, and that some of these contributions might have an economic bearing. Magnetic methods would be of use in this project, inasmuch as it is probable that the “Eastern” sandstone overlying the traps is very thin for some distance from the contact, therefore making it possible to trace the structure of the underlying traps by their magnetic effects.

So far as the part of the district between Victoria and Mandan is concerned, a project of general magnetic mapping is less attractive. The geologic maps accompanying this report furnish for that part of the district a degree of detail and accuracy far beyond the most extravagant ideas of successful outcome of a magnetic survey in a region such as that of the Wisconsin Keweenawan. In other words, the magnetic surveyor would start in this area with a map of more detail and greater accuracy than he ever could hope to make at the end of his work in the Wisconsin Keweenawan area. A certain amount of magnetic work in such well-mapped areas would be of use, however, in gaining an understanding of the way in which the various magnetic effects should be interpreted. Then when magnetic data from large unexplored drift-covered areas, such as those in Wisconsin, are studied, a much greater degree of certainty in their geologic interpretation would be possible.

The methods of magnetic surveying for general stratigraphy are fairly well standardized. Traverses across the formation, usually following land lines, are run at intervals, and the dip-needle readings are taken at equal intervals along the traverses. The distance between traverses should vary with the degree of detail of the information desired and the degree of detail already known. The interval between observations should vary in the same way. In order to make a contribution to the geology of the closely drilled areas, such as La Salle or Delaware-Mandan, magnetic traverses should be run at intervals of, say, one-eighth of a mile or less with readings taken every 25 feet. In the relatively unmapped country, such as that southwest of Victoria, traverses every half mile with readings every 50 feet would probably furnish a degree of detail which would serve as a basis for a fairly good contribution to the local geology.

6. Many problems of a topical rather than an areal nature present themselves as possible subjects of research in which magnetic methods could be used. Among those that have occurred to us are the mapping of the Lake Shore trap, a study of the felsites (present information not being sufficient to determine the intrusive or extrusive character of some of them), the relation of magnetic effects to character and thickness of trap, the distribution of magnetite in the flows, and the relation of magnetic effects to the tops and bottoms of flows.

Department of the Interior
Roy O. West, Secretary

U. S. GEOLOGICAL SURVEY
George Otis Smith, Director

Professional Paper 144

THE COPPER DEPOSITS OF MICHIGAN

BY

B. S. BUTLER and W. S. BURBANK

IN COLLABORATION WITH

T. M. BRODERICK, L. C. GRATON, C. D. HOHL, CHARLES PALACHE
M. J. SCHOLZ, ALFRED WANDKE, and R. C. WELLS

UNITED STATES
GOVERNMENT PRINTING OFFICE
WASHINGTON
1929

ADDITIONAL COPIES

OF THIS PUBLICATION MAY BE PROCURED FROM
THE SUPERINTENDENT OF DOCUMENTS
U S GOVERNMENT PRINTING OFFICE
WASHINGTON, D. C.
AT
$2.50 PER COPY

CONTENTS

ILLUSTRATIONS

PART 3. DETAILED DESCRIPTION OF LODES AND FISSURES

In the following pages the ore deposits are described by lodes and fissures. A description by properties would in some cases cover deposits on several lodes and fissures, and a description by mines would in several cases cover but a part of a lode. The descriptions of lodes are arranged in order of stratigraphic position from higher to lower.

NONESUCH LODE

The Nonesuch lode is present throughout the Copper Range of Michigan, but prospecting and mining in it have been confined to the vicinity of the Porcupine Mountains, mainly around their east end. The White Pine mine is the only one that has made a notable production of copper from the Nonesuch lode. It was the only mine on the lode that was accessible at the time that this study was made, and therefore most of the statements regarding mineralization on the lode are based on observations made in that mine.

STRATIGRAPHIC OCCURRENCE

The Nonesuch lode is near the base of the Nonesuch shale, which lies between the Copper Harbor group and the Freda sandstone and is the highest formation known to be mineralized in the district. The Nonesuch formation is made up predominantly of red and black shales and red sandstone. Near its base is a persistent gray sandstone about 7 feet thick overlain by a thick black shale. Below the sandstone is about 4 to 6 feet of black shale followed by red sandstone and lenses of conglomerate. The gray sandstone underlying the thick black shale, the thin bed of shale below, and a few feet of sandstone below the shale are the most persistently mineralized strata in the formation, but where mineralization has been greatest it has extended to a maximum distance of 75 or 80 feet below the base of the black shale.

The black shale is a rather finely laminated, somewhat chloritic rock. Specimens of the shale from the White Pine mine, when heated in a closed tube, give off the tarry odor of hydrocarbons. The sandstone layers, which are predominantly red, range from medium-grained sandstone through grit to conglomerate, with pebbles several inches in diameter. The conglomerate consists mainly of pebbles of felsite and quartz porphyry and thus resembles the conglomerates of the principal copper district to the northeast. The sandstone of the beds in which the copper occurs is seen under the microscope to be made up of medium to coarse grained fragments, largely subangular. The constituents are quartz, feldspar, epidote, tourmaline, apatite, iron oxides, chlorite, micas, jasper, and fragments of felsite, trap, and volcanic glass in a matrix of finer grains of the same kinds, with calcite, silica, and iron oxides in considerable amount as cementing materials. Changes in the sandstone due to mineralization are mentioned on page 171.

STRUCTURE

Structurally the Porcupine Mountain area is a domical uplift that constitutes a conspicuous irregularity on the south limb of the Lake Superior syncline. Felsite and coarser porphyry occupy the center of this uplift. Around and dipping away from them are the Eagle River group and younger formations, including the formation of particular economic interest, the Nonesuch. The uplift has not merely domed the beds upward but some of the beds have been broken across, so that although the felsite is in contact with the traps of the Eagle River group on the north and northwest sides of the mountains, it is brought against very steeply inclined younger rocks, including Nonesuch beds, on the southeast side.

Irving and later Wright and Lane explained the absence of the older rocks (like the Eagle River traps) on the southeast side of the felsite as due to a fault, called the "main Porcupine fault," along the margin of the felsite. Where the eastern end of this supposed fault is indicated on the original map of Wright and Lane, exploration between the White Pine and Nonesuch mines shows no fault to be present. If the felsite mass is an intrusive, this cutting out of certain beds along its border might be explained as a crosscutting intrusive contact.

The deformation in the Porcupine region may be a result of the injection of an igneous mass from below. The shape and nature of the uplift suggest that the intrusive body assumed the toadstool shape of the forms known as laccoliths. Over 40 years ago Irving recognized this structural similarity, but he concluded that "these mountains owe their existence in all probability to a fold," and thus he was left with the presumption that the felsite is a surface flow. Lane also concluded that both the narrow east-west belt of felsite south of the mountains and the larger body of felsite in the Porcupine Mountains region are effusive.

Lane, however, mentions several small intrusive masses just beyond the northwestern margin of the main felsite area (secs. 3 and 4, T. 50 N., R. 44 W.); also intrusive rocks, including felsites similar in appearance to that in the Porcupine Mountain mass, a few miles to the southeast; and these felsitic masses may be offshoots from a common source.

The structure of the region is probably due to the intrusion of an igneous mass of later age than any of the rocks in which deposits of copper and silver are found.

The indications of intrusive force acting upward and outward are not confined to the general doming of the overlying rocks and to the cutting out of certain beds west of the Nonesuch mine. Inspection of Wright and Lane's geologic map of the Porcupine region (see pl. 14) shows the presence of numerous faults disposed radially across the felsite contact on both the north and south sides of the mountains, and also the pushing outward from the east end of the felsite mass of a fan-shaped block some 3 miles wide from north to south, at the horizon of the base of the Nonesuch formation, and a mile wide at the top of the Lake Shore trap, south of the old Halliwell mine. As marked by the offset in the base of the Nonesuch shale, this block has been shoved eastward for nearly 2 miles.

The geologic details regarding this displaced block are known only along its southern edge, where the explorations of the White Pine mine have revealed certain features clearly. It seems evident that the outthrusting of the block was accomplished by a combination of faulting and of buckling or folding of the beds. Its south or southwest side is bounded by a nearly vertical fault, the White Pine fault, and as indicated on the map and shown by certain drilling explorations, its north side is likewise marked by a fault, which extends eastward from the old Halliwell mine. But on the south side, at least, these faults were developed only after the rocks had been folded so sharply that they broke across, and further dislocation was effected by faulting.

There is a suggestion from the map that farther north similar blocks between faults radially arranged with respect to the east end of the main felsite mass have similarly been shoved out away from the mountain, though to a somewhat shorter distance.

Branching from the reverse White Pine faults as shown in the White Pine mine are numerous minor faults that break the beds in the vicinity of the major faults. The details of these faults are given in the description of the White Pine mine (p. 172).

All the known features connected with this particular part of the region point to the production of the structural features by the intrusion of the igneous core of the Porcupine Mountains and the doming up and outward thrusting of the rocks that were invaded. This general setting helps to an understanding of the details of structure that have exerted a control on the ore deposition in the White Pine mine.

MINERALIZATION

ORE MINERALS

The ore minerals are native copper, native silver, and chalcocite. The native metals occur chiefly as cementing material in the sandstone lodes and as disseminated grains or as flakes lying along jointing planes in the shales. Subordinately they are present in fissures and fault gouges. Chalcocite occurs most conspicuously in small fissure veins, with calcite gangue.

It is also sparsely disseminated in the sandstones and in the shales.

FAVORABLE CONDITIONS

The conditions that have been effective in localizing the ore minerals are the confining effect of relatively impermeable shales, proximity to fractures that acted as channels for the introduction of ore-carrying solutions, and favorable mineralogic or textural conditions of certain beds in the sandstones.

Influence of shale beds.—The lodes are in the sandstone close underneath the thick capping of shale, which acted as a barrier to the rising solutions that deposited the ore. The two beds most widely mineralized are immediately below the shale, separated from each other by a few feet of mineralized shale. At the White Pine mine, where mineralization has been most intense near fissures, certain beds have been mineralized for 70 to 80 feet below the heavy overlying shale, but each of the lower beds has for its hanging wall or roof a bed of sandstone somewhat more shaly than normal, which seems to have acted as a barrier to the rising solutions.

Influence of fissures.—-The deposits at the White Pine mine are closely connected with the White Pine fault and the associated branch faults, as is discussed in detail on page 173. Faults occur also in the vicinity of the Nonesuch and White Pine Extension mines, though there is no definite record of their relation to mineralization. Longyear,[1] who was in charge of an exploration in T. 51 N., Rs. 41 and 42 W., north of the White Pine mine, says: "The drilling here has shown the principal mineralized areas to be in the immediate vicinity of the three northeast and southwest faults." Lane[2] also some years ago pointed out the importance of prospecting along faults in the Porcupine Mountain district. Altogether the evidence seems to point very definitely to the association of mineralization with faults.

The ore-bearing solutions appear to have risen along the faults from a deep-seated source till they reached the heavy shale bed, in which the fault fissures were impermeable owing to the formation of gouge in these soft rocks. Below this impermeable bed the solutions spread out into the more permeable rocks and deposited the ore minerals.

[1]Longyear, C. S., Michigan Geol. Survey Pub. 24, ser. 20, p. 20, 1916.

[2]Lane, A. C., Unexplored parts of the Copper Range of Keweenaw Point: Lake Superior Mining Inst. Bull., vol. 17, p. 133, 1912.

Mineralogic and textural influences.—-The third factor in controlling the distribution of the copper is the physical and mineralogic character of the beds impregnated. In so far as this factor may relate to differences between the particular beds mineralized and other near-by layers of the sandstone, it is believed to be of somewhat less importance than the two factors just discussed—namely, proximity to one of the larger cross faults and an impervious cap rock. Near one of these faults at the White Pine mine the mineralized layer is thicker than it is farther away. Within the lodes the copper is in many places confined to certain beds. Thus a lode 6 feet thick may have most of its copper in two or more layers that together make up not more than one-third of the total. In most hand specimens, and in thin sections as well, the copper is seen to follow certain bedding planes. This habit is undoubtedly due to some favorable textural or mineralogic features of the beds, but these have not been recognized except by the presence of copper associated with them.

The sandstones at the base of the Nonesuch shale, like most sandstones of the Keweenawan series of the Lake Superior region, are predominantly red. The red color is due to the rather plentiful ferric oxide with which the felsitic grains are impregnated and also ferric oxide, which, together with calcite, forms the chief cementing material of the rocks.

The sandstone layers that carry copper have been bleached to a gray or greenish-gray color. Thin sections from the lode at the White Pine mine show that there is not much calcite remaining, but in its place as a cement is a pitchy black hydrocarbon, in an amount reaching a maximum of probably 2 per cent. The greenish tinge in this bleached rock is due to chlorite, which occurs largely as fringes about the sand grains and especially around the edges of the patches of hydrocarbon. The ferric oxide originally present in the unbleached rock has evidently been reduced to ferrous oxide and in part gone into combination as chlorite, but most of it appears to have been removed. This bleaching has occurred whether or not impregnation with copper has taken place just at that point. Many drill records show "gray sandstone" at the horizon of the lodes, but its copper content may be very low.

The impression gained from study of the sandstones in the White Pine mine is that the hydrocarbon, like the copper, has been introduced along the fissures and that its abundance has been determined by the same factors—namely, the presence of an impervious capping, proximity to a pronounced cross fault, and certain textural and mineralogic features of the beds. The hydrocarbon, like the copper, occurs below the shale and shaly sandstone and is distributed through a greater thickness of beds and in greater amounts near the cross faults. It is more abundant in certain layers at these horizons, perhaps in those which were rich in replaceable calcite. The hydrocarbon occurs in the cross faults and fissures to an even greater proportionate extent than the copper; good-sized pieces of 10 to 20 pounds in weight made up largely of hydrocarbon have been obtained from such faults. The hydrocarbon is thought to have a greater horizontal distribution along the lodes than the copper, however, as it is found extending out along the beds farther than copper in commercial quantity.

The source of the hydrocarbon is not known with certainty, but inasmuch as the overlying black shale is bituminous, yielding a tarry distillate when heated in a glass tube, it seems probable that the hydrocarbon has been derived either from this shale or from some similar rock that may lie deeper in the series, by distillation under the heat and pressure attendant upon the intrusion and metamorphism of the region, or perhaps it was removed by the heated waters that carried the copper, although none of the shale seen in the mine appears to be leached or to have lost any of its black pigment.

The genetic relations of this carbonaceous substance and the copper are not entirely clear. Inasmuch as the same general conditions controlled the distribution of each, they are closely associated. The copper occurs in many places as a shell about the hydrocarbon, replacing the chlorite fringe. The period of deposition of hydrocarbon therefore was finished before that of the copper. Furthermore, the massive hydrocarbon of the fault zones is well impregnated with copper; whether this means replacement of the hydrocarbon by copper or simultaneous deposition of the two is not clear.

These relations might be thought to suggest that the hydrocarbon was active as a precipitant of the copper. In all the mines of the main productive region to the northeast, however, copper has been precipitated in the lodes that are high in ferric iron, and the precipitation has been attended by bleaching of the rock occasioned by reduction and removal of the iron but without the slightest evidence that any hydrocarbon has been involved. This is as true of the conglomerate lodes (parts of which are made up of sandstone like the lodes at the White Pine mine) as it is of the amygdaloid lodes. Bleaching of the rock through reduction and removal of the iron is likewise characteristic of the White Pine lodes. It is evident that the copper of the White Pine district entered an environment that would have been favorable for copper precipitation had there been no hydrocarbon present. The facts that copper occurs close to bituminous shale only in the Porcupine region and that so far as known hydrocarbon is associated with copper only in that region, and everywhere close to the shale, lend weight to the view that the hydrocarbon has been derived locally from the shale and at best exerted but a subordinate and modifying influence on the deposition of the copper, if indeed it had any influence at all.

In summary it may be repeated that the textural and mineralogic factors in the localization of the copper are of minor importance. The following generalizations may be made regarding the color of the sandstone and the presence of hydrocarbon and of copper:

1. No copper was seen in red sandstone, although copper occurs in gray bands in red sandstone.

2. No gray sandstone was seen at the White Pine mine without some hydrocarbon.

3. Little if any hydrocarbon was noted in red sandstone.

4. Gray sandstone without copper was noted.

5. The sandstone of the lodes may have been in part rendered gray by the hydrocarbon before the copper had all been deposited.

6. Although there seems to be a close connection between the hydrocarbon and the copper, it may be purely fortuitous; in any case the indications are that the copper solutions entered what would have been a favorable environment for copper precipitation had there been no hydrocarbon present.

7. Here, as in the larger deposits farther northeast, the deposition of copper is believed to have been accomplished by the oxidizing effect of ferric oxide in the rocks upon the copper sulphide solutions. In the fractures themselves, where the contact of the solutions with the rock was less intimate, part of the copper was deposited as native metal and part as the sulphide chalcocite.

WHITE PINE MINE

Location and topography.—The White Pine mine (pl. 33) is in secs. 4, 5, 8, and 9, T. 50 N., R. 42 W., Ontonagon County, a few miles east of the Porcupine Mountains, and is the most southwesterly producer among the mines of the copper district.

In the immediate vicinity of the mine the country, which stands about 200 feet above Lake Superior, is flat and monotonous. The bedrock is buried by glacial drift as much as 160 feet in thickness. The northward-flowing streams have cut rather shallow valleys into the drift and in places have exposed bedrock. These exposures and the drill records show that the rock surface also is one of little relief.

Production.—The White Pine Copper Co. was organized in 1909. Its production and dividends to the end of 1923 were as follows:

Rock stamped ... tons	887, 654
Refined copper produced:	
Total ... pounds	18, 233, 169
Per ton of rock ... do	20. 54
Silver produced ... ounces	260, 681
Dividends paid:	
Total	$33, 438
Per pound of copper ... cent	0. 18

Rocks.—The following section is compiled from the notes of drill hole No. 162, 1,800 feet south of No. 3 shaft, supplemented by the data obtained in the mine concerning the rocks below the Second lode. The members of particular economic importance are indicated by indention.

Section at White Pine mine

	Feet
Red shale	300+
Red sandstone and shale	530
Black shale	300
Brown and black shale and gray sandstone	200
Black shale	70–110
Gray sandstone (First lode)	7
Black shale (parting shale)	6
Gray to red sandstone [3] (Second lode)	7
Red sandstone	13
Gray to red sandstone [3] (lower Second lode)	6
Red sandstone	17
Felsite conglomerate	3
Red sandstone	15
Gray to red sandstone [3] (Third lode)	8
Red sandstone	600+

Structure.—The relation of the structure of the White Pine area to the general structural features of the region is shown on the map of the Porcupine Mountains and vicinity (pl. 14). In greater detail, the structure near the mine is shown in the small map of Plate 33, which shows the contour plan of the first lode, compiled from diamond-drill records and mine workings.

In the neighborhood of the White Pine mine the rocks have been dislocated along a southeast line so that those on the northeast side have been moved southeastward about 2 miles (as marked by the position of the first lode at the level of Lake Superior) and upward probably more than 1,500 feet. This diagonal upward displacement has been accomplished partly by a buckling fold, which accounts for the strong curvature of the lode as it approaches the fault, and partly by faulting, which produces perhaps half of the total horizontal displacement and likewise about half of the total vertical displacement. The White Pine fault is of reverse throw; it dips steeply northeast, and its northeast side, containing most of the mine workings, is the up thrown side.

As this dislocation forms the southwestern boundary of the outthrust block, it is evident that the block on the northeast side of the fault—that is, the block that contains the principal mine workings—moved, and that on the southwest was stationary, relative to the country rock in general. It is probable that the block that moved would suffer greater stresses than the one that remained at rest, and it seems likely that the region of the present mine workings (*I*, pl. 33) is a place of greater disturbance than the region on the opposite side of the fault (*III*). Faulting of the rocks appears favorable for the occurrence of ore in this locality, as is shown below.

[3]Gray where mineralized; elsewhere red.

The minor faults that are numerous in the developed portion of the mine are irregular in strike, dip, and throw, but certain generalizations concerning their behavior can be made. Two principal ones (*N* and *K*, pl. 33), from which many of the others are subordinate branches, are well exposed underground. The existence of another fault of apparently similar direction of strike and throw is suggested by the drill records in the neighborhood of *S*, some 1,500 feet east of No. 5 shaft. The known faults, like *N* and *K*, decrease in amount of throw as distance from the White Pine fault increases. The place at which the suggested dislocation *S* is revealed is distinctly farther from the supposed continuation of the White Pine fault than the farthest known extensions of *N* and *K*, yet the displacement at *S* is greater than the maximum at *N* and *K*. There is a possibility, therefore, that *S* is a larger fault than the others and that nearer to the White Pine fault along *S* there may exist either a single strong fault or a region of disturbance similar to that in the *N-K* block and of even greater intensity.

The known cross faults, with the exception of *K* and a few smaller ones, have their downthrown side to the southeast. As the fault *K* has its downthrown side to the northwest, the greater part of the block of ground between No. 3 and No. 4 shafts has been dropped with respect to the blocks on the northwest and southeast. The faults *N* and *K* have caused a greater displacement of the lodes than any of the others that were traceable for any considerable distance through the mine. Their displacement is variable, but in general they bring the First lode on one side well down toward the Third lode on the other side; this implies some 40 to 50 feet of vertical displacement. Most of the cross faults cause a displacement of less than 10 feet.

These cross faults as a rule are curved rather than straight, and many of them twist surprisingly. They are probably contemporaneous with the major dislocation represented by the folding and by the White Pine fault. The curvature is convex in dip as well as in strike toward the southeast until the faults finally become tangent to the White Pine fault. They branch, horsetail fashion, on the convex side as they swing away from the White Pine fault, and they decrease in amount of throw outward from it. All these facts suggest that these minor cross faults are due to drag along the major White Pine fault in or near a semi-plastic material such as the thick overlying shale.

Mineralization.—-The general features of the mineralization of the Nonesuch lode are described on pages 169-171, but the special relation of the faults branching from the White Pine fault may be pointed out. The evidence of the premineral age of the cross faults lies in the facts that the lodes are thickest and richest in the immediate vicinity of the larger cross faults, and that the cross faults themselves are well mineralized, even the smallest joints and fissures in the sandstone and adjacent shale carrying copper.

The richest ground in the mine is in and immediately adjacent to the block between the principal cross faults, *N* and *K*. Here the lodes are both thickest and richest.

The records of the diamond drilling from the surface give the copper percentages for the several mineralized beds. Multiplying each of these percentages by the number of feet of rock which it represents and adding together these products gives a percentage-foot figure for each hole that represents what may be termed the “intensity of mineralization” of the ground penetrated. To obtain these figures, only the foot ages of ground that assayed 0.5 per cent or more of copper were considered. For example, the intensity of mineralization of a given hole is computed thus:

Material	Feet	Copper (per cent)	Computation
Black shale	80	Trace.	
Gray sandstone	5	1. 6	5×1. 6 = 8. 0
Black shale	6	. 45	
Gray sandstone	7	1. 35	7×1. 35= 9. 45
			17. 45

Plate 33 shows the position of each drill hole together with the intensity of mineralization as thus obtained for it, also contours drawn at 25-unit intervals over the entire area drilled. It is apparent that the block between faults *N* and *K* and the immediate vicinity is by far the richest ground drilled, copper contents and thickness of lodes both being considered.

The evidence of the drill records was confirmed by sampling in the workings of the mine at different intervals, chiefly east of the fault *K*. Over 50 samples were taken, assays for which were furnished by Mr. C. H. Benedict. The places for sampling the several lodes were selected as nearly along the same vertical line as the exposures in the workings allowed. Thus the same method of multiplying percentage of copper by thickness of lode and adding the products gives figures which represent "intensity of mineralization" at different places. These figures likewise show that mineralization is most intense near the fault *K*, grading outward from it toward No. 5 shaft. Minor deviations from the general rule are probably due to the enriching effect of subordinate fractures near points where the assay samples were taken.

Plate 33 shows that shafts Nos. 3 and 4 are in the heart of the only noteworthy ore body penetrated by the drilling. The holes to the northeast and northwest along the outcrop of the lodes indicate that the mineralization is slight there as compared with that in the present workings.

Other evidence indicating that faults *N* and *K* were channels for the mineralizing solutions is afforded by a series of small but very rich ore bodies, including all the rich silver bodies seen, which cling very close to these faults. They are in the nature of thickenings of the normal lodes, and mineralization of two lodes that are not mineralized generally through the mine—namely, the Lower Second lode and the Third lode. The mineralization of the Third lode, so far as now known, is confined to the highly mineralized part of the area, centering about *N* and *K*.

Plate 33 shows that in places outside of the present mine workings where there are breaks in the structural contours, indicating cross faulting, there are increases in the mineralization. Such places are found in the NE. ¼ sec. 6 and the NE. ¼ sec. 9 (fault 8).

To summarize: In the White Pine mine the copper was probably brought in by solutions ascending along the White Pine fault. As these solutions leaked out into the somewhat permeable sandstone, they continued to ascend in the sandstone until they were diverted slantingly upward by the shale barriers. But the movement of solutions was also facilitated by the cross faults, and especially by the stronger ones. By this combination of conditions the favorable portions of the rock were afforded a sufficient volume of solution to become commercial lodes, whereas farther away from the faults the richness falls below the economic limit. Copper or chalcocite was also deposited in the faults and fractures themselves. This relation between faults and the best mineralization is in accord with the experience of those who have worked elsewhere in the Porcupine Mountain district.

Extensions of ore bodies.—Development of the lodes at the White Pine mine has been carried from the outcrop down to the White Pine fault. The lode has been located on the downthrown side of the fault, but development of it has been very slight, and principally at No. 2 shaft. As indicated in the discussion of structure there are some reasons for supposing that the downthrown block may be less broken by branch faults than the up thrown block and therefore less favorable to mineralization. If the solutions were rising along the White Pine fault it also seems probable that the beds on the up thrown side were more favorably situated to receive them.

Diamond drilling shows that the beds associated with the branch fault east of the White Pine mine workings are mineralized at some distance from the main fault, and it seems possible that this mineralization may be more intense nearer the main fault.

WHITE PINE EXTENSION MINE

The following statements regarding the White Pine Extension mine are largely compiled from the records of the company. The mine is in T. 50 N., R. 44 W., about 8 miles west of the White Pine mine. The workings are in the Nonesuch formation south of the Porcupine Mountain uplift. The property has been developed by diamond drilling across secs. 7, 12, 13, and 14, with a total of 45 holes ranging in depth from 80 to 1,400 feet. A shaft has been sunk to a depth on the incline of 438 feet, and drifts have been opened on the No. 2 shale on the second and fourth levels for a maximum distance of 3,380 feet.

The rocks belong to the Nonesuch formation; which, as shown in the drill cores from the Freda sandstone downward, includes the following beds:

	Feet
Brown shale and sandstone	280–380
Upper grit	40– 50
Bedded gray shale group	125–150
Lower grit	10±
No. 1 shale	15±
No. 1 sandstone	6±
No. 2 shale	4½
No. 2 sandstone.	
Red sandstone.	

The beds dip away from the Porcupine Mountain uplift at an angle of 83° in the mine workings. They appear to be regular in the main, though there is minor faulting across the lodes.

Mineralization has occurred mainly in No. 1 shale, No. 2 shale, and a bed in the sandstone about 9 feet below No. 2 shale, known as No. 3 sandstone. At 33 feet from No. 2 shale a crosscut on the fourth evel encountered "quartz-banded shale" with disseminated sulphide which assayed 20 pounds of copper to the ton for a thickness of 3 feet. The copper occurs in the shale mainly as thin sheets and flakes in the bed partings and joints.

Drifts have been opened on No. 2 shale with crosscuts at 100-foot intervals to No. 1 shale and at 200-foot intervals to No. 3 sandstone. When operations ceased in May, 1918, the following work had been accomplished:

	Feet
Shaft, incline depth	438
First level, incline depth	55
Second level, incline depth	220
Third level, incline depth	320
Fourth level, incline depth	420
Drifts:	
First level, 14 feet north, 11 feet south	25
Second level, 1,542 feet north, 1,838 feet south	3, 380
Fourth level, 1,138 feet north, 1,080 feet south	2, 218
Crosscuts	1, 322
	7, 383

No. 2 shale for a width of 4.8 feet, including some barren shale that breaks with the ore, has an average copper content of 21 pounds to the ton. North of the shaft there is some relatively poor ground averaging about 13 pounds to the ton. If this is eliminated, the south ends of the drifts average between 23 and 24 pounds to the ton.

A total of 23 samples of No. 1 shale assaying from 6 to 20 pounds to the ton gave an average of 12 pounds for a thickness of 5.7 feet.

A total of 10 observations on No. 3 sandstone on the second level showed a width of 1.6 to 3 feet and a copper content of 0 to 28 pounds. On the fourth level the sandstone showed no mineralization and in some crosscuts could not be identified.

When the mine was closed water was being pumped at the rate of 92 gallons a minute.

NONESUCH MINE

The Nonesuch mine, about 3 miles west of the White Pine, was productive intermittently from 1868 to 1885, and its recorded production is 389,556 pounds of copper. The mine is developed by four shafts.[4] No. 3, the deepest, went to the fifth level, a depth of 460 feet. The occurrence of the ore, apparently, is similar to that of the neighboring White Pine mine.

ONONDAGA EXPLORATION

The Nonesuch formation was examined by diamond drilling by the Onondaga Copper Co. in Tps. 49 and 50 N., Rs. 42 and 43 W., on the south side of the structural basin south of the Porcupine Mountains. The formation is similar to that on the north side of the basin, but the copper content as revealed by the drilling did not warrant development.

OTHER PROPERTIES

North and northeast of the White Pine mine pits have been sunk in days past on bunches of copper or silver ore in the sandstone, apparently associated with faults. Some of these faults may be of a magnitude corresponding to that of the White Pine fault. (See pl. 14.)

The rocks at the Nonesuch horizon were examined by diamond drilling in T. 51 N., Rs. 41 and 42 W. Some copper was found, and the best ground was reported to be near the faults,[5] but it was not further developed.

LAKE SHORE TRAP HORIZON

The sandstone immediately under the Lake Shore trap is mineralized at several points on the north side of the Porcupine Mountains and was developed years ago in the Carp Lake mine. From 1860 to 1865 there was a recorded production of 33,935 pounds of copper. The copper of this mine has replaced red sandstone immediately below the Lake Shore trap. The sandstone is mineralized from a few inches to a few feet from the trap. Where mineralized, the red sandstone is bleached to gray. No hydrocarbon was noted in this sandstone. On the dump of the Carp Lake tunnel is vein material consisting mainly of calcite and in part an iron-bearing carbonate with included chalcocite.

The sandstone has been shown to be mineralized over a distance of several thousand feet near the Carp Lake mine and is reported to be mineralized at several other points along the north slope of the Porcupine Mountains.

ASHBED AMYGDALOID

The Ashbed amygdaloid (pl. 34) has been prospected from the Atlantic mine, south of Portage Lake, nearly to the end of Keweenaw Point. Whether the developments on this stretch are on the same bed is not known, but they are at the same general horizon, a little below No. 17 conglomerate. The most extensive developments have been made at the Copper Falls, Arnold, and Phoenix mines, in Keweenaw County, and the Atlantic mine, south of Portage Lake.

PRODUCTION

The following table shows the production from the Ashbed amygdaloid to the end of 1925:

Production and dividends from Ashbed lode to end of 1925

Mine	Period	Rock treated (tons)	Copper produced (pounds)		Dividends	
			Total	Per ton	Total	Per pound (cent)
Atlantic	1873–1910	8, 714, 452	118, 282, 028	13. 57	$990, 000	0. 84
South Pewabic	1866–1870		3, 562, 967			
Garden City	1859–1866		75, 397			
Arnold	1898–1900		1, 772, 231			
Copper Falls	1858–1893		*17, 706, 352			
Petherick	1862–1877		*556, 424			
Phoenix	1855–1862, 1865		*357, 032			
Do	1916–1917	48, 063	449, 416	9. 35		
Ashbed	1881–1884		*78, 957			
			142, 840, 804		990, 000	. 70

* Estimated.

[4]Comm. Mineral Statistics Ann. Rept. For 1883, pp. 153-154, 1884.

[5]Longyear C. S., Michigan Geol. Survey Pub. 24, ser. 20, 1916.

CHARACTER OF ROCK

The Ash bed flows are toward the andesitic end of the basaltic series and are everywhere porphyritic, containing rather abundant small feldspar phenocrysts, which are usually collected in nests.

The amygdaloid is prevailingly of the scoriaceous type and is ordinarily cited as the typical example of scoriaceous amygdaloid. There is, however, a notable variation in the amount of the clastic material in the Ashbed at different places. At the Atlantic mine, so far as indicated by the dump material, it is distinctly of the scoriaceous type with pebbles and boulders of amygdaloid in a sandy matrix. At the Phoenix mine the upper part, or "gray" bed, is of the same character, but the lower part, or "red" bed, is not described as scoriaceous. At the Copper Falls mine the bed is locally sandy and approaches the scoriaceous type, but for the most part it is rather typically fragmental. At most of the places in Keweenaw County where it has been cut by the diamond drill the lode is scoriaceous. At the Copper Falls mine it is well oxidized, and at the Atlantic it is said to be chocolate-colored. The Ashbed seems, therefore, to be a fairly well oxidized amygdaloid.

MINERALIZATION

The mineralization of the Ashbed does not seem to differ materially from that of other lodes. The more abundant minerals at the Copper Falls mine are calcite, quartz, epidote, and pumpellyite. Near the fissures datolite is apparently abundant, and in Keweenaw County it appears to be generally more abundant on the Ashbed than on the other lodes.

At the Phoenix mine the basal portion of the lode is chloritized. Not enough of the Atlantic lode has been seen to give a very clear idea of the mineralization. At the Copper Falls mine much of the bleaching associated with copper is of the iron-removal type.

At the Copper Falls mine the upper part of the lode seems to contain more copper than the deeper part, and there is some copper in the basal amygdaloid of the overlying flow. At the Phoenix mine the copper seems to occur throughout the "gray" lode, but the top of the "red" lode is richest. At several places in Keweenaw County where the lode has been cut by the diamond drill the copper seems to be in amygdules in the lower trappy part of the lode.

DEVELOPMENTS

COPPER FALLS MINE

At the Copper Falls mine of the Arnold Mining Co. the Ashbed had been opened in 1891 to a depth of about 1,500 feet and had been opened and stoped for about 2,400 feet along the strike. The workings extend about 1,000 feet east and 1,400 feet west of the Owl Creek fissure. Work continued for a year or so after 1891, but the extent of the latest openings is unknown. The Ashbed was also opened adjacent to the Petherick fissure but to what extent is not known.

The Ashbed lode as seen in the upper levels of the Copper Falls mine is of the fragmental type of amygdaloid with some sandy material and is well oxidized. The width stoped varies greatly but probably averages 6 to 8 feet. The lode seems richest near the top.

A report by Wadsworth states that the lode averaged 10 to 12 feet in thickness and yielded about 1 per cent of copper. The yield in 1859 is given as 22.8 pounds to the ton. There is no record of the output from the Ashbed separate from the output from the Owl Creek fissure, which was operated at the same time, but the production from the Ashbed was certainly considerable.

The relation between the Owl Creek and other fissures and the mineralization of the Ashbed is not very clear, but the mineralization seems to have been strongest near this fissure.

ARNOLD MINE

At the Arnold mine the lode has been opened by No. 1 shaft to the eighth level. On the fifth level a drift has been carried 210 feet to a fissure, which was opened for a short distance. The drift has been extended also about 300 feet south, to a fissure which was opened for about 400 feet. The levels above the fifth were not carried far from the shaft.

PHOENIX MINE

The Phoenix mine of the Keweenaw Copper Co., on the Ashbed lode, was not operating when this report was in preparation. The following notes are taken from the company records and statements by Mr. C. A. Wright, superintendent.

The hanging wall is marked by a clay slip that dips and strikes with the formation. This possibly represents No. 17 conglomerate. Below the clay slip is the amygdaloid of a trap averaging about 15 feet in thickness. Next is the "gray" lode, with a slip at the top. The "gray" lode is described as an amygdaloidal trap that grades downward into dense trap. In places there is sandstone at the top of the "gray" lode, ranging from a fraction of an inch to several feet in thickness; the lode averages 6 to 7 feet. The trap of the "gray" lode is at some places 15 feet thick, but at other places it appears to be absent. Next is the "red" lode, described as amygdaloidal conglomerate with no mention of sandy material. The thickness of the "red" lode averages 15 to 20 feet but is variable. This suggests that the "red" lode here, as at the Copper Falls mine, may be more a fragmental than a scoriaceous amygdaloid. The trap of the "red" lode is about 60 feet thick. The next amygdaloid is described as narrow, and reddish gray; it is mineralized in spots but seems very "bunchy."

The Ashbed is crossed in the Phoenix workings by the Phoenix and Armstrong fissures, and near the surface a third fissure was opened. A fault west of the Phoenix fissure offsets the beds to the east of the fissure about 60 feet to the north.

The Ashbed has been opened at the Phoenix mine to a depth on the dip of 1,600 feet and along the strike for about 2,500 feet. Most of the development has been on the "gray" lode, and most of the production has apparently been from this lode. The copper in the "gray" lode is said to be fine.

From October 13, 1916, to December 31, 1917, 67,215 tons of rock was hoisted, of which 18,993 tons was discarded; 48,063 tons stamped yielded 449,416 pounds of copper, a recovery of 9.35 pounds to the ton, with a loss in tailings of 5.65 pounds to the ton. This can probably be taken as representing the grade of the "gray" lode.

The "red" lode has also been opened in several places, at most of which it is reported to show an encouraging amount of copper near the top of the lode, in a zone as much as 4 feet in thickness. It is said that the copper is coarser than that in the "gray" lode. Some mineralization is reported to have occurred also near the base of the lode. Apparently not enough sloping has been done on the "red" lode to give a clear idea of the copper content. The lode close to the fissures is said to be poor, but there is some suggestion that it may be better in the general vicinity of the fissures than it is away from them.

The Ashbed was also opened at Garden City, east of the Phoenix workings. Old reports indicate that amygdaloids similar to those at the Phoenix were present and that the copper content was encouraging. The production, however, was small. The "red" lode appears to have been the one most worked at Garden City.

HANCOCK MINE

The Ashbed has been opened at the Hancock mine but is described with the other lodes of that mine on pages 177-178.

ATLANTIC MINE

At the Atlantic mine the Ashbed lode has been opened for about 5,800 feet along the strike and down to the thirty-fifth level. (See pl. 34.) Here the lode was of the scoriaceous type, was soft, averaged 12 feet or more in thickness, and seems to have been rather uniform in character and in mineralization in the central part of the mine but became poorer both to the north and to the south. The copper is said to have been rather uniformly distributed through the lode, and the developed ground has been nearly all stoped.

The only structural feature of importance at this mine is a strong fissure or "crossing" with a steep northerly dip extending through the mine just north of No. 2 shaft. The filling of this fissure, as judged by descriptions and some material on the dump, was a coarsely crystalline calcite, in places at least with a pinkish tinge.

It is said that in the upper levels the lode near the fissure was poor, and a rather wide pillar was left. In the lower levels the pillar left was much narrower. In the early years of operation of the Atlantic Mining Co. the rock averaged 18 to 20 pounds of copper to the ton, but for much of the productive period it did not exceed 15 pounds and dropped almost to 11 pounds. For the last years of operation it was as follows: 1902, 11.09 pounds; 1903, 12.78; 1904, 13.63; 1905, 13.72; 1906, 14.69. When the mine was closed by caving in 1906 it was reported that the central portion in the deeper levels shows no indication of a decrease in the grade of ore. The profitable operation of the Atlantic mine on a lode that averaged so low was due partly to the rather uniform mineralization, which made mining cheap, and partly to the softness of the lode, which was favorable to cheap mining and milling.

LODES OF THE HANCOCK MINE

Production from the lodes of the Hancock mine (pl. 35) began in 1861 and continued with interruptions till 1918. The total production from these lodes, together with a considerable production from the Pewabic lodes by the Hancock Consolidated Mining Co. that has not been separated is 17,559,557 pounds. The earlier production, from 1861 to 1886, 5,360,000 pounds, was derived from lode No. 1; and the later production, from 1911 to 1918, 12,199,000 pounds, mainly from lodes Nos. 3 and 4 and the Pewabic lodes. In the later years the yield averaged about 13.5 pounds copper to the ton.

The writers had no opportunity for an examination of the Hancock mine, and the following statements and the accompanying maps and sections are based on data furnished by the Hancock Consolidated Mining Co.

The lodes of the Hancock mine lie between No. 17 conglomerate and the Pewabic lodes. The old No. 1 lode is, to judge from the descriptions and from the course of the drifts along it, apparently on the Hancock fault, a reverse fault which strikes at the surface about N. 54° E. and dips at a considerably steeper angle than the beds. The fault fissure evidently curves very irregularly, both the dip and strike varying greatly from place to place, and it doubtless has numerous branches. The apparent displacement of the beds, measured horizontally at right angles to the strike, is about 600 feet but differs considerably at different points. The actual movement on the fault to produce this apparent displacement was certainly much greater.

No. 1 lode has been opened along the strike for about 1,200 feet and to the fourteenth level. Most of the stoping was done between the surface and the tenth level. There is a strong suggestion of a southerly pitch to the ore shoot.

No. 3 lode is the amygdaloid of the third flow below No. 17 conglomerate and is therefore at the general horizon of the Ashbed amygdaloid. It is, in places at least, scoriaceous and in this respect resembles the Ashbed. The No. 3 lode has been opened for about 1,500 feet along the strike and has been stoped mainly between the tenth and eighteenth levels.

No. 2 lode is the amygdaloid next below No. 3 lode. The lode called No. 9, above the eighteenth level is probably

No. 2 repeated below the Hancock fault. No. 2 lode has been opened for about 1,000 feet along the strike and stoped mainly between the sixth and eleventh levels. The stoping on the part known as No. 9 is mainly between the twelfth and eighteenth levels.

The true No. 9 lode, as it may be called, below the eighteenth level is above the fault and below No. 16 conglomerate. No. 4 lode is a little below this No. 9 lode and probably a little above the Pewabic Far West lodes.

There are, then, two general horizons of mineralization—one represented by lodes No. 2 and No. 3, lying near the horizon of the Ashbed amygdaloid r and the other represented by No. 4 and the true No. 9 which lie below No. 16 conglomerate. In addition No. 1 lode is apparently on the Hancock fault. Most of the ore thus far developed occurred above the Hancock fault.

PEWABIC AMYGDALOID LODES

LOCATION AND PRODUCTION

The Pewabic amygdaloid lodes (pl. 36) have been mined mainly in the properties that now form the Quincy mine. The present Quincy mine (see pl. 74, *A*) includes the Old Quincy, Pewabic, Franklin, Mesnard, Pontiac, and others. Outside the Quincy mine the lodes have been mined in the Hancock mine, adjoining the Quincy on the south and in the Franklin Junior mine to the north. To the south the rocks at this horizon were extensively explored by the Naumkeag Copper Co. and to the north they were opened at the Rhode Island mine and have been cut by the vertical shafts at Calumet but only slightly explored.

The following table shows the production of the Pewabic amygdaloid lodes from the beginning of operations to 1925:

Production and dividends from Pewabic amygdaloid lode, 1855–1925

Mine	Period	Rock treated (tons)	Refined copper (pounds)		Dividends	
			Total	Per ton	Total	Per pound of copper (cents)
Quincy	1856–1861		4, 505, 266			
Do.	1862–1906	12, 897, 426	367, 124, 148	28. 46		
Do.	1907–1910		85, 425, 417		27, 002, 500	3. 74
Do.	1911–1925	14, 371, 072	268, 945, 488	18. 71		
Albany & Boston	1862–1864		14, 982			
Franklin	1857–1860		669, 981			
Do.	1861–1870	457, 450	14, 329, 231	31. 32	1, 240, 000	1. 03
Do.	1871–1883		24, 656, 624			
Franklin and Franklin Junior	1883–1919	[a] 3, 888, 462	[a] 80, 186, 631	[a] 20. 62		
Pewabic	1885–1887		27, 823, 416		1, 000, 000	3. 60
Rhode Island	1903–1906		31, 000			
Hancock [b]						
			873, 712, 184		29, 242, 500	3. 35

[a] Estimated.
[b] Much of the production from the Hancock mine for 1911 to 1918, amounting to 12,199,000 pounds of copper, was derived from the Pewabic lodes.

CHARACTER OF FLOWS

The Pewabic amygdaloid lodes at the Quincy mine consist of a group of relatively thin flows. These overlap so that it is possible to follow amygdaloid continuously and still pass from the amygdaloid of one flow to that of another. It is difficult to correlate the flows certainly from one point to another unless the top of the flow has been actually followed, as one flow may give place to another within a few hundreds or, in the thinner flows, a few tens of feet.

In composition the Pewabic flows fall toward the andesitic end of the basaltic Keweenawan series. Texturally they are glomeroporphyrites and feldspathic melaphyres, with ophitic texture in some of the thicker beds, such as the one below the Pewabic Far West lodes in the lower 50 levels at No. 2 shaft. All or nearly all the beds are porphyritic, containing well-developed feldspar phenocrysts.

CHARACTER OF AMYGDALOIDS

The amygdaloids of all the flows of the Pewabic lodes are characteristically of the coalescing type, though different lodes vary in the degree to which this character is developed, and there may also be a decided difference in its development in different parts of a single flow. Where it is well developed there are from 2 or 3 to as many as 8 or 10 cavernous bands or layers in a lode from 3 to 5 feet thick. It is not uncommon to see these bands continuous along a cross section of the lode for 10 to 15 feet or even more, and in the plane of the lode such layers must form connected openings for tens and probably for hundreds of feet. There is every gradation from the well-banded or layered lode to that in which the vesicles show only a moderate tendency to collect in layers and do not form continuous openings.

Fragmental tops are not characteristic of the Pewabic lodes as a whole. A little fragmental rock occurs at the top of the amygdaloids in many places, and over considerable areas the lode is typically fragmental, though more uniform in thickness than most of the fragmental lodes. A large area of this character is present in the south end of the mine, extending from the seventy-sixth to the eighty-first level and covering an area of 400,000 to 500,000 square feet. A smaller area, so far as opened, is present in the bottom (eighty-first to eighty-fifth level) near No. 2 shaft. So far as observed in the lower levels, the East branches of the series show more fragmental amygdaloid than the West branches. The upper and Intermediate levels were seen in only a few places, but it is stated in old descriptions and by those familiar with the upper levels that the “main” lode was a thick, soft, chocolate-colored lode. Some of it was seen on the twenty-second level between No. 2 and No. 6 shafts, where for the most part it is a typical fragmental lode, showing all the characteristics of that type. The lode thins and thickens from place to place with bulges into the hanging wall and the footwall. Where the lode is thin it tends to become cellular and coalescing.

On the twenty-seventh level between No. 2 and No. 7 shafts the character of the lode alternates between rather tight cellular, tending to coalescing, broken in places into large blocks, and fairly well developed fragmental. The fragmental portions have been stoped and doubtless were considerably mineralized. From observations in and descriptions of the lode in the upper levels it seems probable that large areas of the “main” lode above, say, the thirty-fifth level were fragmental. Some of the other lodes where seen in the upper levels are as distinctly coalescing as any on the lower levels.

The oxidation of the coalescing lodes is less than that of the fragmental lodes, though the tops are distinctly reddened. The fragmental portions of the lodes are moderately well oxidized, though not so highly as many fragmental lodes elsewhere.

MINERALIZATION

The mineralization associated with the deposition of copper in these lodes was simple. Silicification of the lode is pronounced, and quartz is abundant, commonly as well-formed crystals in the open cavities.

Calcite is also nearly everywhere present and rather abundant. Pumpellyite is present as a product of rock alteration and also in open cavities, and epidote is common but less abundant than pumpellyite. Chlorite is abundant in amygdules in the base of the flows and throughout the trap part of some of the flows. Near fissures the chlorite may be replaced by the light-colored minerals, quartz or calcite, which gives the rock adjacent to the fissures a much more amygdular appearance. Zeolites are sparsely represented. Laumontite is present in the Main Spar crossing and was noted in other small fissures. In the lode it is rarely seen on the lower levels but is rather abundant for a considerable distance from the Spar crossing on the upper levels. No other zeolites were noted. Prehnite is present but not common. Nodular masses of porcelanic datolite are said to have been of common occurrence in the upper levels of the mine, but no datolite was seen in the lower levels.

ROCK ALTERATION

The bleaching and alteration of the rock is characteristically of the quartz-pumpellyite type common in the coalescing lodes. In the well-oxidized fragmental portions, especially where seen in the upper levels, the quartz-pumpellyite alteration is less conspicuous and the bleaching is due more to the removal of iron, as in the Kearsage and Osceola lodes.

Before the mineralization, when the cavities were empty, the well-developed coalescing amygdaloid was much more permeable than the cellular amygdaloid and would permit the passage of much more of the mineralizing solutions than the cellular type. It is evidently for this reason that the richer copper ground is in the well-developed coalescing lodes, and although these are not everywhere rich, the poorly developed coalescing and cellular lodes are pretty consistently poor.

Considered in more detail, the coarse copper and masses very commonly are associated with strongly developed bands in an amygdaloid, though the copper and associated minerals generally replaced the rock adjacent to the openings. The finer copper also is as a rule closely associated with well-developed bands, though it may extend some distance from them; and some copper is of course found in cellular amygdaloid and even in amygdules in the trappy portion of the lode.

Fragmental lode rock is of course distinctly permeable and readily replaceable and therefore favorable to mineralization. The masses of such rock exposed in the bottom of No. 2 shaft are pretty consistently rich. The fragmental amygdaloid in the “main” lode in the upper levels of the mine was evidently well mineralized, and in places it was rich. Smaller areas of fragmental lode and areas where a foot or so of the top of the lode is fragmental are commonly good to rich ground. It is pretty clear, therefore, that a fragmental lode in this series can be as favorable and possibly more favorable than a well-developed coalescing lode.

There is some minor fissuring both parallel to and across the lodes. The fissures are commonly mineralized and evidently were favorable to the movement of solution.

MINERALIZATION IN DIFFERENT LODES

The Pewabic lodes are separated into three groups by the Quincy Mining Co. for the purpose of the underground mapping. The grouping is based on position, and the three groups are called the East lodes, the West lodes (including the “main” lode), and the Far West lodes. The East lodes are east of No. 2 shaft in the upper levels. The shaft was in the “main” lode, which apparently corresponds to the West lodes in the lower levels. The Far West lodes are stratigraphically above or west of the West lodes.

The East lodes are the most persistent and regular in the lower and middle levels. They consist of a lower or foot branch and an upper or west branch. The flow whose top forms the lower branch lode rests on the Old Pewabic flow. It is usually not more than 30 to 40 feet thick. It consists in places of one flow, and in places apparently of more than one. The upper flow is even thinner; in places only 10 feet of trap, or even less, separates the two branches, and it is possible that the upper flow is not everywhere present.

In the south end of the mine the upper branch of the lode has been most extensively opened. Stoping on this branch extended from the tenth level, between No. 7 and No. 2 shafts, to the bottom of the mine. To the north there is little work on this branch to the twenty-seventh level in No. 6 shaft, and somewhat lower in No. 8. Below this to about the sixty-fifth level in No. 8 and No. 6 shafts not more than 50 per cent of the lode has been taken. From about the sixty-fifth level to the bottom in the north end more of the upper branch has been taken, and in the south end it has been very largely stoped.

The lower branch was mined but little to about the fortieth level. From the fortieth to about the sixty-fifth level it was extensively mined north of No. 6 shaft, and considerable was taken in the south end of the mine. Below the sixty-fifth level this branch has been mined very little in the south end but some has been taken between No. 6 and No. 8 and considerable north of No. 8.

Above the sixty-third level both branches have in places been mined in the same area, though not as a rule. Below this level in the north end of the mine both have been mined. This difference apparently is due in part to a change in mining method rather than to a sudden change in the character of the lodes.

"MAIN" BRANCH

Down to about the thirtieth level the "main" branch was the one most extensively mined. This is above the East lodes and apparently corresponds to the West lodes in the lower levels. In the lower levels it has been but slightly developed to the north of No. 8 shaft and to the south of No. 7 but has been rather extensively mined from No. 6 and No. 2 in the central part.

There is more than one lode in this West group. What is known as the hanging-wall branch has been most extensively mined. These branches in the lower levels do not seem to have the long stretches of continuous favorable rock that are present in the East lodes, but where favorable rock is present it is very well mineralized.

PEWABIC FAR WEST LODES

The Pewabic Far West lodes have been developed principally below the fiftieth level near No. 2 and No. 6 shafts. In the upper part of the developed area at No. 2 shaft they are separated from the West lodes by an ophitic trap, which is as much as 130 feet thick in this part of the mine, but apparently thins very much down the dip, up the dip, and toward No. 6 shaft. The Far West lodes are above this trap, in the coalescing amygdaloidal tops of several small flows. So far as opened, these tops appear to have shorter stretches of favorable amygdaloid than the East or West lodes, but where their character is favorable they are well mineralized.

[PLATE 75. *A*, Shafts on Kearsarge lode; *B*, Shafts on Winona lode; *C*, North Bluff and shafts and dumps of Calico and Minesota lodes, Michigan mine; *D*, Calumet, showing shafts on Calumet & Hecla conglomerate and Osceola amygdaloid]

In the preceding paragraphs the changes in the lodes in different parts of the mine have been noted in some detail to bring out the idea that in a series of lodes like the Pewabic too much emphasis should not be placed on local changes in character of amygdaloid and copper content of individual lodes in their effect on the favor ability of the series as a whole. It is apparent, so far as the present extensive developments show, that some of the lodes were richer in the upper levels, some in the intermediate levels, and some in the lower levels. Some were most extensively mined in the north end of the developed area and some in the south end. The series as a whole appears to have been about equally productive in the upper and in the lower levels of the mine.

FISSURES OR "CROSSINGS"

A strong cross fissure extends through the mine, dipping north at a high angle (see pl. 36) and crossing No. 6 shaft at the fifty-fifth level. The strike of the fissure, as indicated in the fifty-first level footwall crosscut, is about 10° from right angles with the strike of the lode. This crosscut intersects the Allouez conglomerate and in fact all the lodes cut by it only a short distance from the fissure. Where it crossed the "main" lode in the upper levels little stoping was done adjacent to this fissure, and the lode was evidently poor. This condition continued to about the fiftieth level. Below that stoping was carried close to the fissure, which is said to have had little effect on the copper content of the lode for more than a few feet on each side, and in places good ore is present against the fissure. Where seen in the lower levels the fissure has displaced the lode very little, though the rock is broken for several feet. The fissure filling consists mainly of caleite, laumontite, and quartz. Chloritization and pumpellyitization of the wall rock are conspicuous in and near the fissure but extend only a short distance. Where the "Spar crossing" was seen on the upper levels, laumontite is abundant in the lodes for a considerable distance from the fissure. Pink calcite is the most abundant mineral in the fissure; quartz and epidote are present locally. Copper is present in the fissure wherever examined, and at one place a good-sized mass was seen. The copper content of the fissure has not been sufficient to encourage work on it.

Two other crossings are noted on the mine maps; one of these passes between No. 6 and No. 8 shafts and is about parallel to the main crossing; another crosses No. 8 shaft at the twelfth level and dips about with the north boundary of the ore shoot. Neither of these were seen. The first seems to have had no notable effect on the grade of the lode adjacent to it. The second is mainly outside the stoped area.

FAULTS

The only fault of note that affects the Pewabic lodes is the Hancock fault, which cuts the lodes in the south end of the Quincy mine and in the Hancock mine. This fault is represented in the cross section of No. 7 shaft as crossing the shaft at the fifteenth level and reaching the surface in the hanging-wall side of the shaft. These two points give the fault a dip of about 75°. At the fifteenth level it is marked on the map as having a dip of 76° 30' and a strike of S. 17° 48' W. for a short distance. The fault is more fully described in connection with the lodes of the Hancock mine (p. 177) and shown in the cross section of that mine.

The Allouez ("Albany & Boston") conglomerate, as represented in the old adit, is offset approximately 600 feet on the level. The Pewabic lode on the sixteenth level is indicated as having a similar offset.

FRANKLIN JR. MINE

The production from the Pewabic lode and that from the conglomerate lode in the Franklin Jr. mine were not separately recorded for part of the time. After the closing of the conglomerate lode in 1909 the Pewabic lode produced about 16,000,000 pounds of copper. During this period the yield was about 9 to 12 pounds of copper to the ton of rock.

The writers have had no opportunity to examine the lode in the mine.

The lode has been opened by four shafts, but most of the operations have been conducted from the No. 1 shaft, which extends to the thirty-seventh level. No. 3 shaft goes to the fifteenth level. The lode has been opened for about 3,800 feet along the strike, but most of the development has bean within 1,500 feet-north and 1,000 feet south of No. 1 shaft.

In the upper levels most of the ground stoped was north of No. 1 shaft; in the lower levels the productive ground extended south of the shaft, suggesting a southward pitch of the south boundary of the ore shoot. The ground was stoped over a longer stretch in the lower levels than in the upper, and between the upper and lower levels there was an area in which comparatively little of the lode was sloped.

RHODE ISLAND MINE

The Pewabic amygdaloid has been opened at the Rhode Island mine by two shafts—No. 1 to the fourth level, No. 2 to the tenth level. The openings extend about 2,700 feet along the strike for about equal distances north and south of No. 2 shaft. A few tons of mass and barrel copper has been shipped from the Rhode Island mine. There has been no opportunity for the writers to examine the lode in the mine.

ALLOUEZ CONGLOMERATE ("ALBANY & BOSTON")

The Allouez conglomerate (pl. 37) has been opened and mined at three widely separated localities—at Delaware, at Allouez, and at Franklin.

PRODUCTION

The first production from this conglomerate was made by the Albany & Boston Co. in 1862 at the present Franklin Jr. mine. In 1882 the mine was sold to the Peninsula Copper Co., which operated it till 1892. In 1895 it was sold to the Franklin Mining Co. The Pewabic lode was being mined for part of the period, and there is no accurate record of the total production from the Allouez conglomerate, but it was about 34,500,000 pounds. The average grade of the rock in the later period was between 11 and 12 pounds of copper to the ton.

Work was begun on the conglomerate by the Allouez Mining Co. in 1869. From that time there was alternation of company operation and work by tributers till 1892, when production ceased. The total recorded production from the Allouez mine was 25,786,000 pounds. During the later part of the period the yield ranged from 13 to 19 pounds of copper to the ton of rock.

From 1847 for many years the fissures and the conglomerate lode were worked at Delaware by different companies, usually in the most inefficient manner. Altogether a large amount of money was expended to little purpose. Mills were built near Delaware, and later a railroad was extended to Lac La Belle, where a mill was built. There is no accurate record of the production from the conglomerate separate from the fissures, but it is estimated at about 1,770,000 pounds. The largest output was made in 1883 and 1884, when the rock yielded from about 9½ to 11 pounds of copper to the ton of rock. The recovery was poor, however, and the tailings probably contain as much or more than was recovered.

Production from Allouez conglomerate

Mine	Period	Refined copper (pounds)
Franklin Jr.:		
Albany & Boston	1865–1882	865, 057
Peninsula	1883–1892	6, 624, 991
Franklin	1901–1919	34, 473, 984
Allouez	1869–1892	25, 786, 651
Delaware	1882–1885	1, 770, 570
		69, 521, 253

CHARACTER OF CONGLOMERATE

There has been no opportunity for the writers to examine the Allouez conglomerate as exposed in the mine workings. As seen on the dumps at all three localities it is a moderately coarse felsite conglomerate similar to the Calumet & Hecla conglomerate. From descriptions it appears that lenses of the Allouez conglomerate were well mineralized and some were rich but that much of it was poorly mineralized or barren. The character of the mineralization and of the rock alteration seems to be similar to that of the Calumet & Hecla conglomerate. A feature that is pronounced in the Allouez conglomerate at all three localities is the presence along joints and seams of many dark veins of calcite containing finely divided chalcocite. Similar veins are present on the margins of the Calumet & Hecla conglomerate ore shoot, as at Centennial, but are not common in the main shoot.

FRANKLIN JR. MINE

The Allouez conglomerate has been opened at the Franklin Jr. mine by two shafts from the outcrop—in No. 1 to the twenty-fourth level and in No. 2 to the nineteenth level. The openings extend for about 2,500 feet along the strike, and within this area most of the ground has been sloped. The conglomerate has also been opened below the shaft workings by cross-cuts from the Pewabic

No. 1 shaft from the twenty-sixth to the thirty-seventh levels and here also for a maximum distance along the strike of about 2,500 feet but the proportion of the ground stoped in this area is not so great. The stope map suggests that the main ore shoot in this area pitches south.

RHODE ISLAND MINE

A little shallow work was done on the Allouez conglomerate by the Rhode Island Co.

ALLOUEZ MINE

A map in the report of the Commissioner of Mineral Statistics for 1882 gives developments on the Allouez conglomerate to January, 1883. Three shafts had been opened and the lode developed for a maximum distance along the strike of about 1,700 feet. No. 2 shaft extended to the fourteenth level.

The production was derived mainly from a shoot lying north of a " slide" that reached the surface about 200 feet south of No. 1 shaft and intersected No. 2 shaft at the thirteenth" level. The northern boundary of the shoot, which was mined for 700 to 1,000 feet north of the "slide," appears to have been indefinite.

The mine produced as much copper after 1882 as it had before, but there is no map available showing the position and extent of the later openings.

DELAWARE

At Delaware the Allouez conglomerate has been opened by three main shafts and two shallow ones. No. 1 shaft extends to the ninth level, No. 2 to the tenth level, and No. 3 to the fifth level. The openings extend for a maximum distance along the strike of about 2,500 feet, but the main development has been confined to a distance of about 1,200 feet adjacent to No. 1 and No. 2 shafts. Only a small proportion of the lode within the developed area has been stoped.

LODES IN CLIFF MINE

In the early operations in the Cliff mine considerable attention was given to the ninth amygdaloid or "floor," which was opened to the 90-fathom level and followed by drifts for short distances on most of the levels; on the 80-fathom level a drift was extended west about 500 feet and east about 400 feet. The early reports spoke favorably of the showing in these drifts, but in 1864 a test run showed the rock to average less than 15 pounds to the ton, and work was abandoned. In the report for 1864 it is stated that the copper content decreases away from the fissure. The thirteenth "floor" is also spoken of in the early reports as well mineralized, but very little work seems to have been done on it.

When the mine was reopened in 1906 short drifts were run on amygdaloids in the south end of the mine. Whether all looked favorable or not is not evident. It is stated that some fair rock was taken, but the average was evidently poor.

Later some work was done on amygdaloids in the north end without encouraging results. Apparently no work was done at this time on the ninth and thirteenth "'floors," which were regarded as most favorable in the early days.

CALUMET & HECLA CONGLOMERATE LODE

LOCATION AND EXTENT

The Calumet & Hecla conglomerate (pl. 38) has been opened at numerous places from Portage Lake nearly to the end of Keweenaw Point. In most places it is a scoriaceous amygdaloid with a few inches to a few feet of overlying felsitic sand or grit. Only in the Calumet area has it been shown to be a well-developed felsite conglomerate.

The lode has been developed in the Osceola, Calumet & Hecla, Tamarack, Tamarack Junior, and Centennial mines, now all owned by the Calumet & Hecla Consolidated Copper Co., for a distance of about 18,000 feet along the strike and to a maximum depth of 9,300 feet down the dip. (See pl. 75, *D*.)

PRODUCTION

The Calumet & Hecla conglomerate was discovered in 1864, and production from it began in 1865. The following table shows the production from the lode to the end of 1925:

Production and dividends from the Calumet & Hecla conglomerate, 1865–1925

Mine	Period	Rock treated (tons)	Refined copper (pounds)		Dividends	
			Total	Per ton	Total	Per pound of copper (cents)
Centennial	1869–1882		1, 966, 083			
Do	1897–1898	6, 285	119, 190	18. 96		
Tamarack	1885–1917		379, 971, 101		ª$148,726,051	4. 44
Calumet & Hecla:						
Mine	1866–1925	57, 229, 052	2, 831, 092, 153	49. 47		
Reclamation plant	1915–1925	12, 374, 823	127, 686, 924	10. 32		
Osceola	1873–1880	358, 450	12, 652, 028	35. 30		
Tamarack Junior:						
Tamarack Junior Mining Co	1892–1896		9, 462, 191			
Osceola Consolidated Mining Co	1897–1902	619, 478	12, 404, 000	20. 02		
Total production omitting figures for which no corresponding tonnage is given:		58, 213, 265	3, 375, 353, 670		ª148,726,051	4. 41
Mine production		58, 213, 265	2, 856, 267, 371	49. 07		
Including copper reclaimed from tailings		58, 213, 265	2, 983, 954, 295	51. 26		

ª Estimated.

COMPOSITION

The conglomeratic portion of the Calumet & Hecla conglomerate is made up of several kinds of rock varying somewhat in proportion from place to place. The common varieties are felsite, feldspar porphyry, quartz-feldspar porphyry, amygdaloid, and trap, with other types of rock such as quartzite in small amount. The siliceous rocks make up probably more than 95 per cent of the lode. Amygdaloid boulders, which are most plentiful near the base of the lode, appear to have been derived from the amygdaloid immediately beneath the conglomerate and to have moved but a very short distance. A few boulders of more highly oxidized amygdaloid and of trap are present that may have come from other sources. No indication has been found that the siliceous pebbles were derived from earlier conglomerates. This and the absence of basic pebbles except of the amygdaloid immediately below makes it seem that the conglomerate must have been derived from sources outside the series of flows and conglomerates that make up the immediately underlying part of the series. Nearly all the material of the conglomerate is red to brown in color, so that the general color effect of the unmineralized lode is dark red to brownish red.

There is considerable variation in the quantity of the different types of rock in different parts of the lode. For example, felsite and feldspar porphyries are relatively abundant south of the bar between No, 6 and No, 10 Hecla, whereas north of that bar quartz porphyry is relatively abundant. In the lowrer part of the mine, to the south, the quartz porphyry also seems less abundant. In the upper levels in No. 5 Calumet a light-colored variety of felsite porphyry is especially abundant. This rock resembles in color the felsite intrusive south of Ahmeek, although it is not thought to have furnished material for the Calumet & Hecla conglomerate. A few quartzite boulders were noted in the region of the slope shaft and in North Tamarack. Such a local variation in the composition suggests rather near-by sources for the material.

IRON OXIDE OF THE FELSITES AND QUARTZ PORPHYRIES OF KEWEENAW POINT

The following notes relate to the source of the rather abundant ferric oxide in the lode. The chief purposes of the examinations here summarized were to determine whether the bulk of the iron oxides in the Calumet & Hecla conglomerate were there when the mineralizing solutions entered, or were introduced at an early stage of the mineralization, and to determine what oxides they are.

It is believed that the type of iron oxide and its abundance in the several felsites in place along Keweenaw Point throw considerable light on these questions. Polished surfaces of these felsites show that they all contain hematite to a greater or less extent. In several specimens where the reticulate structure characteristic of the magnetite-ilmenite intergrowths suggested that magnetite might be present, its absence was definitely established by such tests as treating the polished surface with hot concentrated hydrochloric acid and powdering the rock and testing with a magnet. It was shown that beyond a reasonable doubt the chief iron oxide of the felsites from the end of Keweenaw Point to the Porcupine Mountains is hematite.

There is evidence that this hematite is a primary mineral of the felsites. It appears homogeneous under the highest magnification available both before and after treatment with hot concentrated hydrochloric acid, showing no islands of unreplaced magnetite such as are common where hematite has replaced magnetite. The rock contains intergrowths that resemble those of magnetite and ilmenite, but such forms are also assumed by hematite and ilmenite. Many examples of hematite with lathlike form were noted, suggesting cross sections of tabular hematite crystals; these are probably identical with the elongated opaque reddish forms in the felsites and acidic porphyries described by Irving under the name "ferrite." Hematite as a primary mineral occurs at many localities in siliceous and feldspathic rocks, where ferrous iron is absent or present in small amounts. That the ferrous iron in some of the Keweenaw Point felsites is low as compared with the ferric iron is shown by the following analyses.

	Fe_2O_3	FeO
Felsite pebble from Allouez conglomerate, unaltered	4. 88	0. 58
Mount Houghton quartz porphyry	2. 27	. 15
Do	1. 72	. 18
Do	1. 44	. 66
Daly's average quartz porphyry	1. 57	1. 02

IRON OXIDES IN THE CALUMET & HECLA CONGLOMERATE

The chief modes of occurrence of iron oxides in the Calumet & Hecla conglomerate may be classified as follows: (1) Disseminated in rather fine particles in the felsite and quartz porphyry fragments and boulders; (2) in rounded grains in the sandy matrix of the conglomerate and particularly in black bands in the sandstone; (3) as hematite in soft, considerably altered boulders, many of which are iron-rich and form the familiar copper skulls when replaced; (4) as specular hematite in vugs and along planes of weakness.

The available information on these modes of occurrence may be summarized as follows:

1. All the polished sections show that the comparatively unaltered fragments of felsite and quartz porphyry—that is, those that are not softened or bleached—contain hematite in varying amounts, as scattered fine grains. In this respect they are the same, as closely as could be determined, as the felsite in place. The same tests to establish the absence of magnetite were made on such material with negative results.

2. Rounded grains of iron oxide occur plentifully throughout the finer material of the conglomerate. As very little or no magnetic material was found in repeatedly testing the powdered rock with a magnet, it is concluded that these grains consist of limonite, hematite, and ilmenite. This conclusion accords with Palache's determination on the black table concentrates of the conglomerate. It also agrees with the statement of one of the company's chemists who analyzed the dark material of the flotation slimes of the conglomerate, that it is a "dark-red powder and but slightly magnetic." His analysis is as follows:

SiO_2	13. 22
Total iron as FeO	45. 41
Cu	3. 62
CaO	5. 37
MgO	1. 14
TiO_2	6. 46

Many of the larger of these elastic grains of oxide consist of limonite through which run reticulate bars of ilmenite. Two possibilities as to the mineral replaced by the limonite present themselves. In so far as it is detritus from traps, it was probably magnetite. If it is felsite detritus, it may have been originally hematite, as hematite-ilmenite intergrowths are common. It is important in a consideration of the chemical aspect of the origin of the native copper to determine when and how this oxidation of the ferrous iron in the small quantity of magnetite in the conglomerate took place. The outstanding chemical alteration of the rock surrounding copper, both in conglomerates and amygdaloids, is the reduction and removal of ferric iron. Therefore, if oxidation of magnetite took place during the mineralization, it is a reversal of the commonly observed reaction. To test this point the iron oxide in some of the sediments, such as the Great conglomerate at Eagle Harbor, far away from copper deposits, was studied, and the magnetite was found to show the same oxidation to a varying degree, as the magnetite in the Calumet & Hecla conglomerate. Hence the change is independent of copper mineralization and probably took place in part soon after the crystallization of the magnetite in its parent lava flow (see p. 42) and in part during the time it was exposed to weathering.

3. Many pebbles and boulders, soft and much altered, are red with ferric oxide. Some of them contain feldspar and quartz phenocrysts. This hematite seems different, on the one hand, from the finely disseminated primary hematite of the hard felsite and, on the other hand, from the shiny black specular hematite which is to be associated with the recrystallizing effects of the mineralizing solutions acting on the rock. The explanation of the occurrence of these soft oxidized boulders is not clear. That there were phases of the porphyries with more abundant iron-bearing silicates than the prevailing types is probable. Irving describes many Keweenawan quartz porphyries as containing altered augite and says that there are gradations from the highly siliceous phases to the diabase porphyries. Hence, a possible source of these iron-rich boulders is not hard to imagine. The chief difficulty comes in explaining their presence in such a soft oxidized state in the conglomerate. If they were oxidized before deposition, how could they stand up under the rather severe mechanical abrasion to which they would be subjected? If they came to rest as hard, unaltered pebbles but were later softened and oxidized, it would mean more intense weathering than is indicated for most of the conglomerate material, though such pebbles would be presumed to be relatively susceptible to oxidation.

4. Specular hematite is not uncommon in open spaces of various sorts in the conglomerate. It is regarded as a result of the rearrangement of ferric oxide, shown to have been present in abundance before the ore-bearing solutions entered,

CHANGES IN THE IRON OXIDES DURING MINERALIZATION

The effect of the ore-bearing solutions upon the iron oxides is notable. Chemical analyses of bleached and unaltered felsite, study of polished sections of pebbles with bleached portions, examination of hand specimens and the interiors of copper "skulls," and observation of the bleaching on a large scale underground all point to the same conclusion—that the introduction of copper has been accompanied by the removal of ferric iron. Polished sections show that the bleached portions of pebbles, whose unaltered parts have swarms of tiny hematite crystals, are entirely lacking in ferric oxide. Hand specimens show that black iron oxide bands in the unbleached sand largely disappear on passing into a mineralized portion. Similarly, the soft iron-rich boulders, which analyses show may run over 12 per cent of ferric oxide, are bleached and contain practically no ferric oxide where the copper has been introduced.

The effect upon the ilmenite has not been observed in polished section, but the petrographic examination of thin sections indicates that much of it changes to titanite. In an epidotized sand nothing is left of many iron oxide grains but the skeletons of reticulate ilmenite surrounded by a transparent mineral, suggesting that the hematite or limonite went to build the epidote, leaving the ilmenite.

Therefore, while it seems clear that the ore solutions had the power of rearranging the iron oxide, the evidence indicates that the bulk of the iron oxide came in at the time of sedimentation as ferric oxide, much of it as primary hematite from and in the felsite and quartz porphyry. It was removed by the ore-bearing solutions, and this removal bleached the rock and was closely associated with the precipitation of copper.

THICKNESS

The conglomeratic portion of the Calumet & Hecla conglomerate, so far as developed, is distinctly lenticular. The longitudinal axis of greatest thickness extends almost due north from about the collar of No. 1 conglomerate shaft, Osceola mine. Both east and west of this medial line the lode thins but not uniformly. There are several minor axes to the east coming to the surface at No. 5 Hecla, No. 1 Hecla, and No. 2 Calumet. (See pl. 38.)

The lens thins not only to the east and west but to the south or toward the outcrop. As far south as No. 8 Hecla the lode has nearly feathered out to the east, and at most but a few hundred foot appears to have been eroded. South from No. 10 much more of it has been eroded. Along the main axis the conglomerate thickens toward the north, or down the dip, the thicker portion being found around No. 5 Tamarack and in North Tamarack. In passing from south to north the thicker part of the conglomerate lens widens notably, so that a cross section through No. 5 Tamarack would include a width of conglomerate having a thickness of 10 feet or more, at least four or five times as great as a similar section passing through the collar of No. 10 Hecla.

It is apparent that in passing downward from the surface successive sections across the entire lode would contain an increasing amount of rock. This is equally true whether the section is taken parallel to the present surface or at right angles with the major axis of the lode. A rough estimate of the relative amount of lode exceeding 5 feet in thickness at the surface and at the twenty-fifth, fiftieth, and seventy-fifth levels gives the approximate ratio 3:4:7:10.

Sections at right angles to the axis of the lode at equal intervals passing about through No. 10 Hecla and No. 1 Hecla and near Red Jacket shaft give a ratio of about 4:8:11.

TEXTURE

The texture of the lode, like the thickness, varies from place to place, and in a broad way there is a rather close correspondence between thickness of lode and texture. Where the lode is thick coarse material is relatively abundant, and where it is thin fine material is relatively abundant. Thus, where the lode is less than 5 feet thick it is composed largely of coarse to fine sand; where it is more than 10 feet thick it is prevailingly a pebble to boulder conglomerate. The portion of intermediate thickness, over considerable areas at least, as is seen in the upper levels of the Calumet and of Hecla shafts Nos. 1 to 5, is intermediate also in texture, the prevailing rock being a coarse grit to fine pebble conglomerate. In the coarser parts of the conglomerate there is a varying but usually rather large percentage of coarse to fine grit that forms the matrix for the pebbles. The coarse and fine phases of the conglomerate, including sandstone, do not differ greatly in composition except that the finer portions contain considerable ferric oxide and ilmenite in grains. In the sandstone these form definite bands that are practically everywhere noticeable, but the grains are also present in the fine matrix of the coarse types of the conglomerate. The finer parts of the conglomerate are therefore richer in ferric oxide and in ilmenite than the coarser parts.

There are coarser and finer phases of the conglomerate present in practically every section. Thus, it would be hard to find a section that did not contain some bands of sandstone, and in the finer beds there are lenses of coarser material. There is no very clearly recognized regularity as to the stratigraphic position in the lode of the fine and coarse material. It is common to find sandstone on the footwall, on the hanging wall, or in intermediate positions, and, on the other hand, the coarser phases may occupy all these positions.

The general impression gained from looking at the lode as exposed in drifts is that the bedding is essentially parallel to the walls. Where mineralization has followed the bedding, however, so that the mineralized rock is prominent for relatively long distances, there is a distinct appearance of cross-bedding of large pattern. Where best seen the divergence of bedding planes is to the north, parallel to the axis of the conglomerate. Cross-bedding of small pattern is seen here and there but is not common.

HANGING WALL

The hanging wall of the conglomerate over a large part of the developed area is a dense trap with a rather pronounced basal amygdaloid, from 2 to 6 inches in thickness, and with pipe amygdules extending upward from the contact of the conglomerate. The basal amygdaloid is commonly slightly oxidized for 1 inch to 6 inches from the contact. The actual contact is slightly irregular, the lava being molded around boulders in the conglomerate.

In the northeastern part of the mine there are frequently 1, 2, or possibly 3 small flows above the main conglomerate lode. In places felsitic sand or conglomerate overlies the small flows. On the twenty-ninth level, south of No. 5 Calumet, the drift follows a 3 to 4 foot bed of felsitic sand resting on a 3 to 4 foot lava flow that in turn rests on the main conglomerate lode. In No. 4 Calumet the hanging-wall flow was recognized as low as the forty-ninth level. The flows have been recognized to the south as far as No. 2 shaft. A small hanging-wall flow (about 15 feet thick) is also present on the sixty-sixth level of the slope shaft where the crosscut extends to No. 3 Tamarack.

It would appear that small flows are present, locally at least, over a considerable part of the area north of No. 2 Calumet and above the sixty-sixth level. The small flows commonly show some oxidation and in places are rather well oxidized.

FOOTWALL

The footwall of the conglomerate is everywhere a scoriaceous amygdaloid, but it differs notably in different places. Over considerable areas there may be from 6 inches to 4 feet of soft red basic sandstone or shale immediately beneath the felsitic conglomerate. Nearer its base this sandstone or shale begins to contain pebbles or boulders of amygdaloid, which gradually become more abundant, and within 3 or 4 feet it passes into scoriaceous amygdaloid filled with sandstone and shale; this in turn gives place to amygdaloid with decreasing amounts of clastic material, and the amygdaloid passes into the footwall trap. The felsite conglomerate may rest on rock of any one of these lower types, suggesting that where the upper members are lacking they have been removed by erosion. The data available do not indicate any very definite distribution of the different types where they form the immediate footwall. The sandstone and shale are, however, rather abundant where the lode thins out to the northeast and also to the south where the lode has been observed—namely, on the forty-ninth and fiftieth levels, south of No. 12 Hecla; likewise where the lode is thin on the seventh level east and west of No. 6 Hecla. These occurrences suggest that in a broad way erosion has been relatively slight where the conglomerate lode is thinnest.

The footwall along the main axis of the conglomerate however, does not seem to show vigorous erosion, as the scoriaceous amygdaloid is present. There seems, indeed, to be little evidence of vigorous erosion at the base of the conglomerate, although the scoriaceous amygdaloid is itself evidence of erosion and deposition at this horizon. The line of separation between the felsitic sediments and the underlying amygdaloid is usually sharp. Pebbles and boulders of the underlying amygdaloid are present in the lower part of the conglomerate, but rarely is felsitic material mingled abundantly with the basic sands of the footwall. The presence of the boulders of amygdaloid in the base of the conglomerate suggests that there has been some erosion and that the finer portions have been carried away or so disseminated through the conglomerate that they are not recognized. Beneath the thicker parts of the conglomerate the amygdaloid is usually dark and shows little oxidation. Where the conglomerate is thin, the amygdaloid is commonly distinctly reddened by oxidation.

STRUCTURE

Faults.—But one pronounced fault zone crossing the conglomerate lode has been recognized. This zone is at the surface between Nos. 3 and 4 Hecla and crosses the seventy-ninth level about 400 feet north of No. 6 shaft. The fault has not been cut outside the lode, and the strike can not be closely determined, but it seems to be essentially at right angles to the strike of the lode. The dip is everywhere steep but not uniform. If the strike is at right angles to the lode the average dip is about 82° S. The horizontal offset on this fault on the upper and lower levels is about 8 feet. The same is reported for the upper levels of Tamarack No. 1. The block south of the fault moved to the west. There is a rather strong gouge on the fault in the hanging-wall trap, which has been mineralized with calcite, laumontite, and copper.

Over a zone of 100 feet on each side of this fault there are minor faults with a throw of not more than a few inches where observed. Another faulty which has been traced for several hundred feet, crosses the lode at the crosscut from No. 5 Tamarack on the eighty-first level. This fault strikes at a low angle with the lode, about N. 45° E., and dips northwest. Where observed, the dip is irregular, ranging from 60° to 90°. The hanging wall is up about 6 feet; therefore the fault is reverse.

Not uncommonly there is a slickensided zone on the footwall or hanging wall of the conglomerate. This indicates some movement, but nowhere is the amount known.

Fissures and joints.—Fissures and joints are abundant throughout the conglomerate lode. Many of them can be traced into the footwall or hanging wall, but show no displacement. They are commonly nearly vertical and at right angles to the lode. They are more abundant in certain areas, but close inspection over a few feet of lode almost anywhere will disclose fissures or joints. Many of them contain copper and calcite, and the adjacent rock is bleached, indicating that they are earlier than the mineralization. On a few of these joints a little chalcocite occurs, closely associated with the calcite, and where the lode was opened at Centennial small calcite-chalcocite veins were rather abundant.

ALTERATION

The conglomerate, where unmineralized, is dark reddish brown, the prevailing color being due to the presence of ferric oxide both in the pebbles and as small grains in the finer matrix and in the sand. Where copper is not present the lode has a rather uniform appearance and seems to have suffered little alteration since its burial by the hanging-wall flow. The epidotization of some of the lean ground, especially along the borders of the ore shoots, is an exception which is mentioned on page 188.

SOFT BOULDERS

In parts of the conglomerate soft boulders are rather numerous. These usually contain phenocrysts of red feldspar and quartz and appear to have been similar to the quartz-feldspar porphyry that is abundant in the conglomerate, as pointed out by Pumpelly and others. At present they show rather diverse characteristics. In many of them a soft reddish-brown to dark greenish-brown material incloses the phenocrysts. These appear to be rich in iron, much richer than any of the fresh quartz-feldspar porphyry pebbles. In other pebbles a soft green chloritic material incloses the phenocrysts.

Nearly all the pebbles are softened and altered to the center and give no evidence of the original character of the rock except for the phenocrysts. A few have relatively hard centers. In some of these epidote is abundant, suggesting that the original rock was first highly epidotized and later altered to its present condition. In others there appears to be little or no epidote. Magnetite, barite, and secondary specularite have been noted in these hard centers. As the soft pebbles appear to be as abundant in the rock that contains no copper as in that which is well mineralized with copper, there seems no reason to connect this alteration of the pebbles intimately with copper mineralization.

The soft pebbles are usually in close proximity to other pebbles of quartz porphyry that show no similar alteration. This must mean either that there was some strong selective action or that the soft pebbles were altered in whole or in part before they were incorporated in the conglomerate. That they were incorporated in their present soft condition seems hardly possible. It may be that they had undergone some alteration and were in a condition to be further altered readily when they were incorporated, and that they were softened and oxidized before the conglomerate was buried. No satisfactory explanation of these pebbles has yet been suggested.

MINERALIZATION

CHARACTER

The most striking and characteristic feature of the mineralization is the pronounced bleaching of the rock that accompanied the deposition of copper. At nearly every place where the lode is exposed the presence of copper is indicated by the pale brick-red or salmon color of the mineralized portion as contrasted with the dark brownish red of the unmineralized lode. In the finer material the small pieces of rock may be largely bleached to the center, so that the lode has a rather uniform color. In the coarser material the pebbles have been bleached for a short distance from the surface, but the inner part retains its original color.

The coarser copper is commonly in the cement where it has partly replaced the rock material. Where the rock is bleached, an examination of the polished surface generally discloses the presence of copper. Bleaching not plainly connected with copper has been noted only in lenses of epidotized sandstone. In such lenses pebbles may show a bleaching similar to that associated with copper, and such lenses are commonly surrounded by a narrow zone, rarely more than 1 inch wide, of bleached rock.

The bleaching associated with the deposition of copper has resulted from a removal of ferric oxide. Commonly there is no evidence of the ferric oxide having been converted to another mineral that has remained. There are, however, two exceptions. Sandstone lenses have been almost completely changed to epidote, apparently from a combination of the ferric oxide with other constituents of the sandstone to form epidote, though some of the epidotized sandstone is higher in iron than the corresponding unepidotized sandstone. Copper is commonly present in these lenses, but it is rarely abundant.

The second exception is possibly the alteration of the iron-rich boulders to form “skulls” of copper. In this replacement the portion of the boulders rich in ferric oxide close to the copper has been altered to a soft gray to green material that appears chloritic. There has been a large removal of iron, but some remains as ferric or ferrous silicate.

MINERALS

There are few minerals in the conglomerate that can be regarded as gangue minerals in the sense that they were deposited with the copper.

Calcite is abundant in the lode, but its distribution does not seem to be closely connected with the distribution of copper.

Epidote, like calcite, is rather abundant, though usually not in the rich ground. It is in places plentiful near the margins of ore shoots, and it occurs around many areas of calcite, suggesting that the lime was obtained from the calcite and the ferric oxide from the conglomerate. It is perhaps most conspicuous where it has replaced lenses of sandstone. Such lenses are present in many parts of the mine, though they are decidedly more numerous where the ground is poor. In the conglomerate lode there is no indication of close association of epidote with rich copper ground.

Red feldspar is present throughout the mine in variable amounts. Like calcite and epidote, however, it shows no close association with rich ground, though copper is commonly present with feldspar. It seems rather more abundant on the lower levels.

Barite occurs characteristically in the soft iron-rich pebbles, locally in their bleached portions, associated with copper. Barite in such pebbles is common in the lower levels of the Hecla, but it was rarely seen in the north end of the mine.

Chlorite is rare in the conglomerate except in the soft iron-rich pebbles, where chloritic minerals of undetermined composition are common; also in the altered amygdaloid pebbles.

Zeolitic minerals are characteristically absent from the conglomerate lode. Fissures passing from the lava to the conglomerate lose their zeolites at the contact.

DISTRIBUTION OF THE COPPER

The characteristic occurrence of the copper is in lenticular shoots flattened in the plane of the lode. The mineralized beds may occur in any part of the lode, as near the hanging wall, near the foot wall, or in intermediate positions. In the upper part of the mine, where the lode is relatively thin, the mineralized portion may form a large percentage of the lode. In the lower levels, where the lode is thick, the mineralized portion may be only a relatively small part of the total thickness.

There are no obvious differences in the original characters of the mineralized and the unmineralized parts of the lode, and it seems probable that slight differences in permeability may have been the chief determining factor in producing the deposits. Mineralization may be influenced, however, by variations in composition, the effect of which may conflict in places with that of permeability. For example, it has been pointed out that the finer material contains more ferric oxide and ilmenite as grains than the coarser material. In the alteration of the lodes the smaller particles are completely bleached, while the pebbles are but partly bleached. It would follow that the finer sediment contains more ferric oxide available for reaction, and if this is a factor in the precipitation of copper, it would seem that, other things being equal, the finer-grained parts of the lode would be more favorable. On the other hand, the sandy portions are presumably not favorable to free circulation of solutions. There is then probably some combination of sufficient permeability and abundant iron oxide that is most favorable to precipitation of copper.

INFLUENCE OF FAULTS AND FISSURES

The lode is crossed by one rather strong persistent fault and by a great number of joints and fissures that show little or no displacement. The large fault and many of the joints and fissures are mineralized. Some very handsome specimens of arborescent copper have been taken from the large fault. There is no good evidence, however, that any of these were channels that admitted the ore-forming solutions to the lode. A zone of poor ground lies immediately north of the large fault, through part of the mine at least, but the ground to the south of it is generally good. This difference suggests that the gouge may have acted as a dam against ore solutions moving from the south through the conglomerate and thus caused a lean' area north of the fault. There is little recognized evidence that the ground is particularly rich where the joints and fissures are abundant or particularly lean where they are few. Many of the fractures, however, are bordered by a zone of bleaching and were evidently channels for mineralizing solutions within the lode.

The crosscuts disclose many strike fissures outside the conglomerate that contain calcite, quartz, chlorite, laumontite, red feldspar, prehnite, and copper. A few cross fissures similarly mineralized have been noted.

The position of the lenses of mineralized ground in the lode is distinctly suggestive of solutions moving upward through the conglomerate.

MINERALIZATION OF WALLS

The basal amygdaloid of the hanging-wall trap locally contains some copper. It is said that in the northeastern part of the mine the thin amygdaloida beds were in places sufficiently mineralized to have been taken for ore. Certain joints in the hanging wall contain sheet copper.

Ordinarily there is no copper in the footwall immediately below the conglomerate. Where mineralized conglomerate rests on the basic sand or on the scoriaceous amygdaloid the mineralized rock cuts off sharply at the contact. In the lower part of the amygdaloid, however, there is in many places a little copper. This is associated with chlorite, and the occurrence is similar to that near the base of the Kearsarge amygdaloid.

Where the conglomerate is very thin or lacking and the amygdaloid is moderately oxidized, as on the forty-ninth level south of No. 12 Hecla, the amygdaloid may contain more copper. Here it is associated with bleached areas, and the occurrence, in general, is similar to that of the amygdaloid lodes.

CHANGE IN GRADE OF ORE

From the surface to the lower levels there has been a very pronounced decrease in the grade of the rock. Several possible causes for this decrease are suggested—that the precipitation of copper was controlled by distance below the surface that existed when the deposits were formed; that the decrease is due to a change in character of the conglomerate; or that deposition was influenced by the contraction of the conglomerate body upward. It is possible that all these causes and perhaps others have been operative.

There is little doubt that distance below the surface existing at the time of mineralization was a factor in determining where deposition of copper began. Doubtless there was a range of depth in each lode that furnished the conditions of heat and pressure most favorable to deposition, and probably the deposition was less both above and below that region.

Parts of the lode are physically and chemically more favorable than others. The finer rock, provided it permitted free passage of the solutions, would seem to be more favorable than coarse conglomerate. This may, in part, account for the very rich ground in the upper levels of the Calumet mine, where the conglomerate is fine, and it may likewise account for the low grade in some of the thick parts of the lode.

The conglomerate as developed is a tapering body, increasing both in thickness and in width, and consequently in volume, down the axis. It is roughly estimated that the relative amounts of the conglomerate at the surface and the twenty-fifth, fiftieth, and seventy-fifth levels are in the ratio 3:4:7:10. This upward contraction of the body and consequent decrease in the volume of conglomerate suggest that the change in grade may be due in part to the converging of the ore-depositing solutions through a steadily decreasing volume of rock. It has been found that sections across the shoot at different levels, as the twenty-fifth, fiftieth, and seventy-fifth, contain approximately the same amount of copper, but that in the lower levels the ore, being distributed through more rock, is of lower grade.

The grade map (pl. 38) shows very clearly that there is a steady decrease in the grade of the rock from the surface downward and that in general the successive belts of different grade lie roughly parallel to the present surface.

By far the richest rock in the mine is in the "pocket" lying between the north boundary of the ore body and the bar of thin conglomerate between No. 5 and No. 10 Hecla shafts. From this bar north rich shoots come to the surface between the small bars of thin conglomerate. This relation suggests that there were minor outlets through these channels. Below the bar of thin conglomerate—that is, below the twenty-fifth level—the grade belts are nearly horizontal except in the South Hecla, where good ground extends up along the main axis of the conglomerate body.

In the lower levels of the mine a bar of poor ground with a general northerly trend lies just south of No. 5 Tamarack shaft. This broadens to the north. Likewise, a bar of poor ground seems to come in at the northern extension of the North Tamarack workings, though the facts necessary to outline this ground are not available.

MAP SHOWING "COPPER PER UNIT AREA OF LODE"

The data on which the maps showing grade of rock and thickness of lode are based have been combined on Plate 38 by multiplying pounds of copper to the ton of rock at each point by the thickness of lode at the same point and dividing the product by the number of cubic feet of rock to the ton, thus obtaining figures that represent the amount of copper per square foot of lode at the different points.

An examination of this map indicates that the areas of maximum mineralization do not coincide with the areas of richest rock. The area of maximum mineralization trends northward and down the lode, roughly parallel to the main axis of the conglomerate body but somewhat above it, and the mineralization decreases in intensity northward and down the axis. There are some exceptions to these general tendencies. The most pronounced are a tendency for the intensity to increase in the pocket toward the outcrop of the Hecla, and the presence of a rather large area of relatively low mineralization in the vicinity of the lower workings of the Tamarack.

An attempt has been made to determine the relative amounts of copper in different horizontal cross sections of the lode. This has been done by multiplying the "foot-pound" figure (obtained by multiplying pounds per ton by thickness of lode) by the length of lode on the sections at the different levels. One estimate took the general average for the level as the "foot-pound" figure; another estimate calculated each line in several sections, which were combined to obtain the "foot-pound" figure. The greatest difference, on the seventy-fifth level, resulted from differences in estimate on the undeveloped area at the north end of that level and may be taken as representing the uncertainty as to that area.

The average of the two estimates gives the following relative amounts of copper on the different levels, in a unit section: Twenty-fifth, 133; fiftieth, 133; seventy-fifth, 115; average, 127. The seventy-fifth level thus shows 10 per cent below the average.

It is apparent, then, that so far as these data are trustworthy they indicate a decrease in mineralization with increase in depth, though the decrease shown is certainly not beyond the limits of error in the data used. What they seem to show with considerable certainty is that the tendency toward a decrease in total mineralization with increase in depth is not marked, but that the large decrease in grade is due mainly to the dissemination of approximately the same amount of copper through a larger volume of rock.

A calculation of the amount of copper in the lode from the data indicated on the maps, with the assumption that 75 per cent of the lode has been stoped, gives approximately the amount that has been actually recovered and thus tends to corroborate the approximate accuracy of the data used on the maps.

If it is assumed that the same amount of copper is disseminated through the lode at each level and further that the grade at the seventy-fifth level is 30 pounds to the ton, then at the fiftieth level it should be 43 pounds, at the twenty-fifth 75 pounds, and near the surface 100 pounds. The recorded grades show a rather surprising approach to these figures.

There seems no reason to expect a change in these general relations with increased depth. The lode appears to be increasing both in extent and width, and it would follow that there should be a decrease in grade of ore. There does, however, appear to be some tendency to break up more with depth into poor and rich shoots. The appearance of the lode underground suggests this rather more strongly than the data brought out on the map.

CAUSE OF CONVERGENCE OF SOLUTIONS AND INFLUENCE OF BARRIERS

As pointed out on page 101 and indicated on the map showing thickness of lode (pl. 38) the part developed is a projection from a much larger body of conglomerate. As no striking relation has been found between fissures and mineralization, it is believed that the solutions gained entrance at some point below the area developed and rose along the lode. If movement were unimpeded the solutions would probably rise directly along the lode toward the outcrop. If, however, they met a barrier they would be deflected and move upward below the barrier.

It is of interest, then, to note what such barriers may be. As is well known, the finer a sediment the less readily a solution moves through it. Toward the edges of the conglomerate lenses the material becomes finer, and where the lode is less than 5 feet in thickness it is mainly sand. There appears to have been little movement of the solutions through these sandy parts, and they may be regarded as under the circumstances effective barriers to the movement of the solutions. The favorable influence of the converging barriers on the grade of ore is discussed under "Ore shoots" (p. 115).

COPPER BOULDERS AND SKULLS

Many of the pebbles of porphyry rich in iron and others largely altered to a chloritic material that lie in the ore shoots have been very favorable to replacement by copper. Pumpelly long ago described the characteristics of the pebbles thus replaced. The inner part of the pebbles and presumably the part least affected by the copper solutions is a red porphyry. The material varies considerably but is commonly rather soft and friable, dark red-brown to greenish black, and evidently rich in ferric iron. Next to the copper of the "skulls," which are only thin envelopes of copper surrounding the pebbles, is a zone of gray-green soft chloritic rock, which grades into the red central part. There is much less iron in the chloritic part of the pebbles, and much of that present is ferrous iron.

In other pebbles the copper penetrates to the center and only a small proportion of the rock material remains.

This consists of phenocrysts of feldspar and quartz and some green chloritic material similar to that described above. The feldspar is somewhat altered, but the nature of this alteration has not been determined.

SILVER

Very little silver was seen in the conglomerate lode. That observed, principally in the southern stopes on the lower levels of No. 10 Hecla, is similar in mode of occurrence to the amygdaloid. It seems to be slightly later than the copper. It is said that silver was much more abundant in the upper levels of the Hecla shafts.

OSCEOLA LODE

HISTORY AND PRODUCTION

Important production from the Osceola lode in the Osceola mine began in 1879 and continued without interruption for any whole year till 1920. Exploration on the Osceola lode by the Calumet & Hecla Co., began in 1895 and steady production in 1904. The following table shows the production from the lode from the beginning of operations till the end of 1925.

Production and dividends from Osceola lode, 1879–1925

Company	Period	Rock treated (tons)	Copper produced (pounds)		Dividends	
			Total	Per ton of rock	Total	Per pound of copper (cents)
Osceola Consolidated	1879–1923	9, 513, 943	190, 787, 393	20. 05	[a] $14,789,825	3. 63
Calumet & Hecla, Osceola branch	1904–1925	14, 598, 914	213, 817, 584	14. 65		
Centennial Copper Mining	1891	28, 531	531, 983	18. 64		
Do	1892		106, 801			
Do	1897–1900	153, 662	1, 917, 901	12. 48		
Tamarack Mining			[a] 9, 237, 000			
		24, 295, 050	416, 398, 662		14, 789, 825	3. 55
Production omitting figures for which no corresponding tonnages are given		24, 295, 050	407, 054, 861	16. 75		

[a] Estimated.

OSCEOLA FLOW

The Osceola flow (pl. 39), which is a well-marked ophite, has been traced with a reasonable degree of certainty from the Arcadian to the Cliff mine. Outside this stretch there is doubt of the accuracy of suggested correlations.

At the Cliff mine the flow is 35 feet thick; at the Ahmeek, 130 feet; at the Red Jacket shaft, seventy-eighth level; 210 feet; at the LaSalle, 180 feet; at the Franklin Jr., 98 feet; and at the Arcadian, 129 feet. It is the thickest part of the flow, near Calumet, that thus far has been productive. In this respect the Osceola is like the Kearsarge flow.

CHARACTER OF THE OSCEOLA AMYGDALOID

The Osceola flow throughout the area that has been extensively developed, and probably over a much larger area, has a distinctly rough or fragmental top. Its surface, which is much more irregular than that of the Kearsarge flow, consists of a series of hummocks and depressions of very irregular shape and variable size. Perhaps the tops of the hummocks and the bottoms of the depressions would average 12 to 15 feet above and below an average plane, or 25 to 30 feet from top of hummock to bottom of depression. In places the variation is considerably greater, and of course in other places it is less.

The lode is distinctly of the fragmental type. There is less of the nonfragmental, cellular lode rock than in the Kearsarge flow, but where present it commonly underlies the fragmental rock, as in the Kearsarge. The coarse cellular rock that is very common in the lower part of the Kearsarge lode is also less abundant in the Osceola. In many places the lode passes directly from fragmental lode to fine foot trap. There are areas where the lode is mainly of a rather thin cellular type.

There are considerable areas of the lode that contain much sandy material and are of the “scoriaceous” type.

Inclusions of partly resorbed amygdaloid are present below the lode, but they are scattered and not a conspicuous feature of the footwall as they are of the Isle Royale lode.

THICKNESS

The lode ranges in thickness from as little as 1 foot to as much as 60 feet; perhaps in a few places it is even thicker. In general, the lode is thicker in the hummocks, consisting mainly of fragmental rock, that rise above the average level of the top of the flow, and is thinner in the depressions below the general level, as the fragmental material commonly extends deeper under the hummocks than it does under the depressions. This is what would be expected if the fragmental material floated in irregular masses on the lava—the higher the loose solidified material was piled above the general level the deeper it would sink into the liquid or plastic part of the flow, and it would remain there when the whole came to rest and solidified. It is the lower portion of these downward bulges that constitutes the so-called “foot lode.”

In places the lode contains a bar of “vein trap” with fragmental rock above and below. This, however, has rarely been seen to be continuous over very large areas. Ordinarily the fragmental material underlying the thin trap layer is connected near by with that on the top of the flow, and in most places the lode is simply a continuous thick mass of fragmental rock.

The lode also shows variations that are on a larger scale than those mentioned above. Bands of relatively thick and thin breccia pitch in a southwesterly direction, in general, parallel to the southern boundary of the Osceola ore shoot. Such a thin band is rather consistently present along the south boundary of the Osceola shoot, and similar bands are present in both the Osceola and the Calumet & Hecla portions of the lode. Within these thin and thick belts the minor variations of hummocks and depressions are present.

HANGING WALL

The hanging wall of the Osceola lode is a heavy trap with a rather indistinct contact between its thin basal amygdaloid and the upper surface of the Osceola lode.

In many places the hanging wall is jointed and sheet copper is present on the joints. In both of these features—namely, the lack of a clear-cut upper boundary and the presence of copper in the hanging wall—the Osceola differs from the Kearsarge lode.

STRUCTURE

Except for the features of the lode itself, the structure in the Osceola mine is simple. There is no noteworthy folding or faulting, and only relatively few small fissures cross the lode.

ALTERATION AND MINERALIZATION OF THE LODE

Oxidation.—In its general character the oxidation of the Osceola lode does not differ from that of other fragmental lodes. As in the other lodes, it is earlier than and independent of the copper mineralization and varies with the character of the rock. The highly fragmental lava is consistently well oxidized; the cellular and trappy rock is much less oxidized.

There is not the same change in degree of oxidation from the hanging wall toward the footwall in the Osceola that there is in the Kearsarge lode. The Kearsarge lode is most highly oxidized near the trap, but the Osceola lode is highly oxidized throughout—some of its fragmental "foot lode" is apparently oxidized as much as any other rock in the lode. Oxidation has extended rather deeply into the "foot trap," which for some distance from the lode is distinctly redder than the "hanging trap." In this respect, as in some others, this lode resembles the Isle Royale lode.

Alteration and mineralization later than oxidation.—The results of the alteration and mineralization of the lode that were later than the oxidation do not differ in general from those of the Kearsarge lode. Prehnite and datolite are more abundant than in the Kearsarge. Epidote is distributed throughout the Osceola lode, whereas in the Kearsarge it is largely confined to the upper part. This is apparently a result of the deep oxidation of the Osceola lode.

Bleached rock very similar to that of the Kearsarge lode is associated with the copper and differs from that found in the Pewabic, Isle Royale, and Baltic lodes in containing a relatively small amount of pumpellyite.

The more abundant minerals are feldspar (rather irregularly distributed), calcite, quartz, epidote, pumpellyite, chlorite, and prehnite. Prehnite is most abundant in the sandy areas. The less abundant minerals, which are rather unevenly distributed, are datolite, most plentiful toward the south boundary of the ore body; laumontite, mainly in fissures; analcite, also largely in fissures; and a little saponite in the lode.

DISTRIBUTION OF COPPER IN THE LODE

Distribution through thickness of the lode.—In the Osceola lode, as in the Kearsarge, by far the richest and most uniformly mineralized portion lies against the hanging wall. The mineralized rock, however, extends irregularly downward, in places 50 feet or more from the hanging wall. No quantitative data are available as to the relative amount of copper at different depths in the lode, but the general impression is that the top 4 to 5 feet contains fully 75 to 80 per cent of the copper that is present in the upper 10 feet of lode and that the 1 foot just below the hanging wall is by far the richest part of the lode. The copper that lies deep in the lode is irregularly distributed. It is confined to the areas where the fragmental rock extends to considerable depths, but there is too little information as to the grade of rock from the foot workings to determine whether or not copper is always or usually present in commercial quantities in those areas.

Five samples of red lode rock that showed no copper on ordinary inspection were taken to determine if copper is present in rock in which it is not readily seen, and, if so, in what amount. Assays of these samples ranged from 2.8 to 4.8 pounds to the ton, with an average of 3.76 pounds.

As a general rule, "thick lode" and "deep foot lode" occur where the lode bulges up into the hanging wall and, conversely, are not to be expected where the hanging wall bulges down into the lode. If experience shows that copper in commercial quantity is present in a sufficient number of places where "deep foot lode" occurs to warrant prospecting for it, then this relation to the hanging wall would seem to offer a very economical method for locating the areas of thick lode.

Distribution in the plane of the lode.—It has already been noted that there are bars of thin amygdaloid pitching southwest in the lode. These bars are usually poor in copper, though their thicker portions contain some commercial ground. Along the south boundary of the ore shoot, where it has been examined, the lode seems to be rather uniformly thin and tight. This thin streak is regarded as an inclined barrier that has prevented the direct upward movement of the ore solutions along the lode and caused a concentration beneath it. This belief is supported by the fact that south of this barrier the lode is lean, even though it is moderately or even in places decidedly thick and has the other physical characters that are regarded as favorable.

The best ground in the shoot has in general been found close to the barrier, and the grade has decreased with increasing distance from it; but the grade varies notably with the character of the lode, and too little definite information is available to give a very clear picture of the variations and their causes. The following facts, however, have a bearing on the matter.

In the lower levels there is a notable change in the grade of rock northward from the south boundary. The area south of Osceola No. 6 shaft is of decidedly better grade than that of No. 5 shaft. In the accessible levels near the bottom of No. 5 the lode is of only medium thickness, a condition which was probably a factor in producing the lower grade, but regardless of the difference in character of lode, there seems to be a decrease toward the north in general, which is observed in the Calumet & Hecla Co.'s Osceola ground as well as in the Osceola mine. Taken as a whole, there is a decrease in the grade northward, till in No. 18 shaft there is a much lower proportion of pay rock than in the south side of the shoot, and in the Centennial it apparently was not sufficient to encourage development below the twelfth level. A shaft farther north in Wolverine ground is apparently out of the shoot and encountered no encouraging copper content to the fifth level. Tamarack No. 1 in its upper levels encountered some commercial rock, but this continued for only a few levels, when the rock became of too low grade to pay.

The available facts thus suggest that the commercial rock will be found to fail toward the north along a line roughly paralleling the southern boundary of the ore shoot. This means, of course, that the shafts from the north to south will reach unprofitable ground at progressively greater depths. No. 18 even at the outcrop is at about the margin of pay ground. No. 17 averaged poor below the tenth level. No. 16 seems to be getting leaner in the lower levels. If this trend continues, No. 15 will soon be getting into poorer ground, though the Tamarack found some good ground between Nos. 15 and 14 at considerably greater depth. Nos. 14 and 13 would seem to have a good distance to go before they encounter poor ground.

No. 5 Osceola is bottomed in rather poor ground, and the question naturally arises whether this is the bottom of the shoot. The general trend would suggest that it is not. Furthermore, there is a rather wide bar of thin lode in Calumet & Hecla ground that, if projected, would about intersect the bottom of No. 5 shaft, and it is possible that the poor grade in the bottom of No. 5 is in part due to this bar of poor, thin lode rock, and that the bottom of the shoot is at very considerably greater depth.

VARIATION IN COPPER CONTENT WITH DEPTH

In any discussion of the variation of the copper content of the Osceola lode with depth, it is necessary to consider the ore shoot as a whole and not a section as represented by any single shaft. Considering individual shafts, there is little doubt that all the Calumet & Hecla shafts and Nos. 1, 2, and 3 Osceola would eventually show a decrease in copper content with increase in depth. Nos. 5 and 6 Osceola, on the other hand, pass through lean or nearly barren ground for several hundred feet before entering the ore shoot, and there are indications that the ground along No. 5 shaft is growing leaner in the lower levels.

If, however, an inclined belt parallel to the trend of the ore shoot is examined—for example, a belt 1,000, 2,000, or 3,000 feet north of and parallel to the south boundary of the ore shoot—no clear evidence is found of a decrease in copper content with increase in depth down the shoot. The grade of the ore recently mined in the lower levels of the Osceola mine is lower than that of the ore formerly mined in the upper levels, but this is, in part at least, a matter of changes in mining method and policy, as is discussed below, rather than a real change in the copper content of the lode.

There are no exact data available to check the grade of the ore in different parts of the mine, but the impression gained from inspection of the lode is that the copper content of the rock in the ore shoot in the lower levels south of No. 6 shaft compares favorably with that in the higher levels of the mine.

CHANGES IN METHOD OF MINING

There have been decided changes in the method of mining lodes of this type in the district and in the Osceola mine itself, as is very evident to one going through the workings of different periods and of different depths of mining. In the early days of mining on the Osceola lode the method seems to have been to make the highest possible recovery from the hanging side of the lode; the hanging wall was stripped clean, and the pillars were small. No great effort was made at that time to get a high recovery of the copper deep in the lode. A relatively narrow stope was carried against the hanging wall, and where copper was exposed near the footwall it was apparently followed; but where it was not exposed little if any effort was expended in search for it. Thus there was a high percentage of recovery from the hanging side of the lode and a low recovery from the foot side.

Moreover, in the early mining a much larger proportion of the thin and poor portions of the lode was left untouched than in the later operations. The ore under this early type of mining over a distance of 2,000 to 3,000 feet north of the south boundary of the shoot yielded 22 to 29 pounds of copper to the ton.

In the lower levels of the mine—south of No. 6 shaft, for example—the width stoped averages distinctly greater than in the upper levels, and more of the lode has been mined, despite the facts that there has not been the former high recovery of the rock just below the hanging wall, a few inches to a foot of lode being commonly left on the hanging wall, and that the pillars are more numerous and larger than in the upper workings, as is required by the greater depth.

The results of this change from the earlier method are not very certain, but the impression is that considerably more lode rock has been mined per unit area, with perhaps little if any greater recovery of copper per unit area. For example, say the average thickness mined in 1920 was 12 feet, including foot work, with a recovery of 18 pounds to the ton, or about 18 pounds to each square foot of lode; in the early mining 8 feet of lode was mined with a recovery of 27 pounds to the ton, or 18 pounds to the square foot.

KEARSARGE LODE

HISTORY AND PRODUCTION

The earliest notable production from the Kearsarge lode was made in the Kearsarge mine, now the North Kearsarge, in 1887, though development had begun some years before. Production from this mine was followed by that of neighboring mines—namely, the Wolverine in 1895, the South Kearsarge in 1900, and the Centennial and Calumet & Hecla in 1904. At the north end of the lode the Mohawk began production in 1903, followed by the Ahmeek in 1904, the Allouez in 1905, the Gratiot in 1910, and the Seneca in 1921. Prospecting has been extended to the north by the Ojibway, Cliff, Miskowabic, Manitou-Frontenac, and Keweenaw Copper (Mandan) companies and to the south by the Laurium, La Salle, and Franklin Jr.

Production and dividends from Kearsarge lode to end of 1925

Mine	Period	Rock treated (tons)	Refined copper (pounds)		Dividends	
			Total	Per ton	Total	Per pound of copper (cents)
Ahmeek	[a] 1887–1925	------	16, 795, 681	------	[b] $29, 782, 000	4. 15
Do		10, 801, 252	241, 492, 186	22. 36		
Allouez		4, 918, 843	82, 222, 989	16. 72		
Centennial		2, 261, 890	33, 033, 675	14. 60		
Calumet & Hecla, Kearsarge branch		2, 331, 524	67, 351, 569	28. 89		
North Kearsarge		------	21, 237	------		
		10, 344, 447	160, 862, 279	15. 55		
South Kearsarge		6, 427, 605	115, 156, 251	17. 91		
Gratiot	1910–1920	30, 315	313, 848	10. 35	------	------
La Salle	1910–1920	739, 624	7, 814, 730	10. 57	------	------
Mohawk	1902–1925	14, 014, 050	259, 114, 348	18. 49	10, 750, 000	4. 15
Ojibway	1911	7, 448	49, 662	6. 63	------	------
Seneca	1920–1924	148, 530	3, 561, 922	23. 98	------	------
Do	1925	17, 313	284, 241	16. 4	------	------
Wolverine	1882–1886	------	1, 979, 378	------	10, 350, 000	5. 48
Do	1891–1925	8, 468, 263	186, 817, 729	22. 06		
		60, 511, 104	1, 176, 871, 725	------	50, 882, 000	4. 32
Production omitting figures for which no corresponding tonnages are given	------	60, 511, 104	1, 158, 075, 429	19. 14	------	------

[a] Mines now belonging to the Calumet & Hecla Consolidated Copper Co. [b] Estimated.

KEARSARGE FLOW

EXTENT AND CRITERIA FOR RECOGNITION

The Kearsarge flow (pl. 40) has been recognized from Atlantic to Mandan, in Keweenaw County, a distance of about 35 miles. The rock is a well-developed ophite. The identification of this flow is commonly based on the porphyritic character of its upper portion and on its position immediately above the Wolverine sandstone. With these aids it can be recognized more easily and certainly than most of the other flows.

The plagioclase phenocrysts are usually most abundant in the trap just below the amygdaloid, though they are present in the amygdaloid. They vary considerably from place to place, both in size and in abundance. Usually the tabular crystals do not exceed half an inch in length and make up but a small part of the rock. Locally, however, they reach an inch in length and over short stretches may form a considerable percentage of the rock. In the "west flow" they are less abundant than in the main flow. The concentration of phenocrysts at the base of the amygdaloid appears to have resulted from the rising of the crystals through the molten lava till they reached the solid or viscous portion near the top, where they were stopped. The lesser numbers in the thin "west flow" may be due to the fact that they collected from a smaller volume of lava.

What is classed as the Kearsarge flow does not everywhere consist of a single flow; in many places there are two or more flows at the Kearsarge horizon that contain feldspar phenocrysts and are grouped as Kearsarge. In the principal productive area, from the Centennial mine to the Gratiot mine, the amygdaloid of the lowest flow of the series has been mined, and only locally have the amygdaloids of the "west lodes" been shown to contain copper in paying quantity. In this area the higher flows are relatively thin, phenocrysts are few, and the amygdaloidal tops are of the cellular type and usually but little oxidized.

THICKNESS

At No. 2 shaft, Ahmeek, the basal Kearsarge flow is 200 feet thick at the surface and has essentially the same thickness in the crosscuts on the Mass fissure in the lower levels. On the twelfth level, Centennial, the Kearsarge trap is 179 feet thick, with 6 feet of amygdaloid, a total of 185 feet. At the surface the total thickness of the flow as scaled from a cross section is 170 feet. The crosscut in the Wolverine mine shows the Kearsarge bed about 200 feet thick. Between No. 1 and No. 2 shafts, Mohawk, on the twenty-first level, the flow is 185 feet thick. It thus seems that in the main productive area this basal flow has a thickness of 170 to 200 feet. Locally overlying the basal flow are thin flows of the Kearsarge type. How much of the lode is covered by such flows is not known, but there are certainly places where none are present, and in other places as many as half a dozen flows are present between the basal Kearsarge and the next heavy trap. These flows are usually thin, but a flow 85 feet thick, with phenocrysts, lies on the main Kearsarge flow at No. 4 shaft, North Kearsarge, and a flow of similar thickness has been noted in a crosscut on the Mass fissure in the Ahmeek mine. It appears, therefore, that in the productive area the Kearsarge flows may reach a total thickness of 300 feet.

The following observations were made north of the more developed area:

Gratiot: No. 2 shaft, amygdaloid 29 feet, trap 169 feet, total 198 feet; No. 1 shaft, amygdaloid 9 feet, trap 193 feet, total 202 feet.

Seneca No. 1 shaft: Diamond-drill hole No. 6, more than 127 feet in five flows; basal trap 63 feet. Diamond-drill hole No. 3, 74 feet from top cut, five amygdaloids and base of series not reached. Diamond-drill hole No. 1, basal trap more than 84 feet, sandstone not reached. Diamond-drill hole No. 5, 950 feet north of No. 1 shaft, 113 feet of Kearsarge flows with four amygdaloids, basal trap 24 feet. The old Seneca No. 1 shaft is sunk near the Wolverine sandstone, and crosscuts were extended from it into the hanging wall. First level, crosscut 150 feet; second level, crosscut 50 feet, drift on an amygdaloid; third level, crosscut about 350 feet, apparently cutting the entire series of Kearsarge flows, drift about 700 feet, apparently on top amygdaloid; fifth level, crosscut about 230 feet, drift on an amygdaloid, possibly the top amygdaloid.

Ojibway: Kearsarge apparently consists of two or more flows. Basal flow at No. 1 shaft reported 35 to 85 feet, at No. 2 shaft 260 to 360 feet.

Cliff: Diamond-drill hole No. 1 at shaft, Wolverine sandstone 33 feet, trap 93 feet, amygdaloid 6 feet, trap 28 feet, amygdaloid 7 feet (west lode?). Diamond-drill hole No. 11, 1,900 feet along strike from south boundary, Wolverine sandstone 2 feet, basal trap 107 feet, amygdaloid 22 feet, second trap 7 feet, second amygdaloid 10 feet, followed by a series of small flows. Diamond-drill hole No. 12, Wolverine sandstone 3 feet, basal trap 46 feet, amygdaloid 5 feet, second trap 12 feet, amygdaloid (Kearsarge) 14 feet, third trap 7 feet, amygdaloid (Kearsarge) 8 feet. Diamond-drill hole No. 3, 5,200 feet north of south boundary, Wolverine sandstone 19 feet, basal trap 174 feet, amygdaloid (Kearsarge) 24 feet, second trap 81 feet, amygdaloid 11 feet. Diamond-drill hole No. 4, 5,600 feet north of south boundary, Wolverine sandstone 5 feet, basal trap 113 feet, amygdaloid 18 feet, second trap 77 feet, amygdaloid 13 feet.

Central mine: Kearsarge as scaled from a cross section, 235 feet in three flows. Diamond-drill hole No. 2, Wolverine sandstone thin, basal trap 70 feet, amygdaloid 5 feet, second trap 57 feet, amygdaloid (Kearsarge) 33 feet.

Manitou-Frontenac: Diamond-drill hole No. 7-4-S, Wolverine sandstone 6 feet, basal trap 28 feet, amygdaloid 4 feet. Diamond-drill hole No. 3-5-S, Wolverine sandstone thin, basal trap 19 feet, amygdaloid 5 feet, second trap 63 feet, amygdaloid 3 feet, third trap 39 feet, amygdaloid 5 feet, fourth trap 21 feet, amygdaloid 14 feet, total Kearsarge flow 169 feet.

Mandan: Diamond-drill hole No. 9, Wolverine sandstone thin, basal trap 55 feet, amygdaloid 6 feet; appears to be one flow.

From the records given above it is apparent that north of the Gratiot mine the basal Kearsarge flow becomes decidedly variable in thickness, ranging from 24 feet in diamond-drill hole No. 5, Seneca, to 260 feet or more in No. 2 shaft, Ojibway, 19 feet in the Frontenac, and 27 and 45 feet at Mandan. In contrast with the main productive area, the basal flow is in most places thin, and the whole series does not maintain the thickness of the basal flow in the area from the Gratiot to the Centennial mine.

The following observations were made south of the productive area:

Laurium: Diamond-drill hole No. 3, 1,700 feet south of north boundary, Wolverine sandstone 10 inches, basal trap 110 feet, amygdaloid 10 feet, second trap 4 feet, amygdaloid 2 feet. Diamond-drill hole No. 2, 800 feet north of shaft, Wolverine sandstone 3 feet, basal trap 141 feet, amygdaloid 8½ feet. Diamond-drill hole No. 4, 900 feet from extreme south boundary, Wolverine sandstone 10 feet, basal trap 144 feet, amygdaloid feet, second trap 4 feet, amygdaloid 7 feet.

Calumet & Hecla: Eighty-first level crosscut, Red Jacket shaft, two small flows over the main Kearsarge lode; basal flow 181 feet.

La Salle: Diamond-drill hole No. 12, opposite No. 2 shaft, Wolverine sandstone 2 feet, basal trap 131 feet, Kearsarge amygdaloid 9 feet, trap 75 feet. No. 2 La Salle shaft is on first amygdaloid. Diamond-drill hole No. 13, 1,700 feet south of No. 2 shaft, from top down, hanging-wall trap 60 feet, top Kearsarge amygdaloid 4 feet, trap 15 feet, amygdaloid 4 feet, trap 20 feet, amygdaloid 14 feet, trap 20+ feet; Wolverine sandstone not noted. Diamond-drill hole No. 14, 250 feet down dip from No. 13, hanging-wall trap 65 feet, Kearsarge amygdaloid 4 feet, Kearsarge trap 33+ feet. Diamond-drill hole No. 1, 5,200 feet south of No. 2 shaft, at No. 5 La Salle, Wolverine sandstone 7 feet, basal trap 28 feet, amygdaloid 4 feet, second trap 28 feet, amygdaloid 6 feet, third trap 10 feet, amygdaloid 12 feet, fourth trap 29 feet, amygdaloid 1½ feet, fifth trap 2½ feet, amygdaloid 6 inches, sixth Kearsarge trap 4½ feet, amygdaloid 7 feet. Diamond-drill hole No. 4, at No. 6 La Salle, Wolverine sandstone, first flow, lowest Kearsarge trap 42 feet, amygdaloid 3 feet; second flow, trap 8 feet, amygdaloid 7 feet; third flow, trap 14 feet, amygdaloid 4 feet; fourth Kearsarge trap 14 feet, amygdaloid 7 feet; hanging-wall trap I 14 feet. Diamond-drill holes Nos. 6, 9, 10, 1,500 feet south of No. 6 La Salle; diamond-drill hole No. 9, Wolverine sandstone 1 foot, basal trap 96 feet, amygdaloid 2 feet, second trap 37 feet, amygdaloid 4 feet, hanging-wall trap 62 feet.

Franklin Jr. mine, thirty-second level crosscut: Wolverine sandstone 10 feet, basal trap (broken) 10 feet, amygdaloid 16 feet; second flow, trap 22 feet, amygdaloid 30 feet.

Franklin Jr. new shaft: First Kearsarge amygdaloid 7 feet, trap 28 feet; second Kearsarge amygdaloid 6 feet, trap 33 feet; third Kearsarge amygdaloid 9 feet, trap 2 feet; Wolverine sandstone (?) 4 inches.

Arcadian No. 1: Total flow 109 feet; No. 2, total flow 101 feet.

Naumkeag: Diamond-drill hole J, Wolverine sandstone 1 foot, trap 57 feet, amygdaloid 17 feet.

Isle Royale mine: Wolverine sandstone 1 foot, trap 49 feet, amygdaloid 5 feet.

Atlantic: Wolverine sandstone 6 feet, trap 40 feet, amygdaloid 17 feet.

From these observations it is apparent that south of the Centennial mine there is a thinning of the Kearsarge flows, and that south of Nos. 1 and 2 La Salle the basal flow is thin and the series generally consists of a succession of thin flows.

CHARACTER OF KEARSARGE AMYGDALOID

GENERAL FEATURES

Next to the Pewabic, the Kearsarge lode is the most regular of the large productive lodes of the district, yet it varies notably in character from place to place. In the main productive area the amygdaloid can be roughly separated into material of three types—namely, “fragmental lode,” banded amygdaloid, and “foot lode.”

The “fragmental lode” consists of irregular angular to sub angular fragments of amygdaloid. The amygdaloid fragments are predominantly fine and contain very numerous but small amygdules, indicating relatively rapid solidification; but mixed with the fine fragments are some of coarser texture.

In the Kearsarge lode as a whole individual fragments rather rarely exceed a foot in greatest dimension, and most of the fragments range from 6 inches to a fraction of an inch. In the top portion the fragments average smaller than toward the base. In position “fragmental lode,” if present, is always at the top, immediately beneath the hanging-wall trap. It gives place downward either to cellular banded amygdaloid or to “foot lode;” if the former, the transition is likely to be gradual; if the latter, it is more likely to be abrupt.

The thickness of the “fragmental lode” probably averages 5 to 6 feet but ranges from 20 feet down to the vanishing point. Very commonly, where the “fragmental lode” is thickest it bulges into the hanging wall, indicating that it formed slight elevations on the surface that was buried by the overlying flow, and it also extends deeper into the underlying material at such places.

The banded amygdaloid, as contrasted with the “fragmental lode,” is an unbroken rock body over considerable areas. The amygdules are commonly more abundant at certain horizons, giving the rock a banded appearance in cross section. In texture it varies with distance from the surface of the lode. Where it forms the top of the lode the upper portion is fine textured and it increases in coarseness with increase in distance from the surface. Where it is covered by “fragmental lode” the finer-textured part is not present. Evidently the “fragmental lode” offered the same protection from rapid cooling as the chilled upper portion of the banded amygdaloid.

The banded amygdaloid may lie immediately below the hanging-wall trap or it may grade upward into “fragmental lode.” Downward it grades into “foot lode.” In most places it is less than 6 feet thick, but it may exceed that thickness locally, as in some parts of the upper levels of the Wolverine, North Kearsarge, Mohawk, and other mines.

The rock in the zone between the banded amygdaloid and the footwall trap is called “foot lode.” It differs from the banded amygdaloid in having a coarser texture, with larger and fewer amygdules and less tendency for the amygdules to form in bands. It grades upward into cellular amygdaloid or underlies “fragmental lode.” In a very few places it immediately underlies the hanging-wall trap. Downward it grades into the footwall trap. Locally it contains a few fragments of cellular amygdaloid. It rarely exceeds 6 feet in thickness.

From the foregoing statements it is apparent that the lode may consist of “fragmental lode,” banded amygdaloid, and “foot lode”; of “fragmental lode” and “foot lode”; of banded amygdaloid and “foot lode”; or rarely of “foot lode” alone. The thickest parts of the lode always comprise a fragmental layer and in many places all three types. The thin parts probably consist most commonly of banded amygdaloid and “foot lode,” though a lava-cemented fragmental thin lode is a common type.

The average thickness of ground stoped varies somewhat in the different mines of the Kearsarge lode. In several of the mines the lode has been so largely removed from the part developed that it is possible to estimate roughly the average thickness stoped from the quantity of rock produced and the area mined. Such estimates are shown on page 199.

The amount of ground left in stoping differs considerably in different mines; it probably ranges from 10 to 35 per cent. The South Kearsarge has one of the highest recoveries, and its greater stoping width as calculated is probably due in part to that fact. For the Mohawk the actual stoping width is said to be about 12 feet, whereas the calculated width is 9.5 feet, indicating that about 20 per cent of the lode is left.

It appears from the calculations that the average thickness of lode stoped decreases from the South Kearsarge northward. That this difference can not be attributed to stoping wider than is warranted in the South Kearsarge and part of the Wolverine is indicated by the average high yield in copper per ton of rock from these mines. It must of course be recognized that there is a decided variation in the thickness of lode in different parts of individual mines. In the Mohawk, for example, the lode averages distinctly thicker at the south than at the north end.

The largest area of thin and cellular amygdaloid in the productive part of the Kearsarge lode extends along the outcrop from about the north boundary of the South Kearsarge to the Mohawk mine. For much of the distance it extends but a few hundred feet below the outcrop, but in the North Kearsarge and Wolverine mines it reaches as deep as the twentieth level. (See pl. 40.)

Another large body of cellular rock is present in the north end of the Mohawk mine. At the surface it extends from about No. 4 shaft to the north boundary, and in the bottom levels from about No. 2 shaft to the boundary. Interspersed with fragmental rock the lode rock of this type apparently extends beyond No. 1 Gratiot shaft, though the lode in that area has been less developed. It is also predominant north of the new Seneca shaft in the deeper levels. Fragmental lode rock occurs along the Mohawk-Gratiot boundary in the upper levels of No. 2 Gratiot, and smaller areas in the upper and intermediate levels of No. 1 Gratiot and in the lower levels of the new Seneca shaft. A third body of cellular lode is found in the lower levels north and south of Allouez No. 1 shaft, and a smaller body is present north of No. 2 Allouez. Another stretch of thin lode is present in the North Ahmeek, extending from No. 4 shaft northward along the Mohawk boundary beyond No. 4 Mohawk. The bodies of thin lode included in the general area of thick lode thus far outlined have their greatest extent along the strike of the lode and relatively small extent on the dip. If this pattern proves to be typical, it may be possible to get some idea of the distance through a thin bar from its extent along the strike.

LOCAL OBSERVATIONS

At Ojibway, according to Hubbard,[6] there is an east lode and a west lode that are copper bearing. Both seem to be irregular in thickness and to be cut out in places. Hubbard suggests that the lode has been eroded and that the old stream channels are recognizable. According to his description the lode is present in the channels and absent from the bounding ridges. To account for this Hubbard[7] suggests that after the erosion of valleys they were partly filled with rock material, which was later covered by the flow. Apparently there are two rather persistent copper-bearing lodes separated by trap. The report for 1909 states that at No. 1 shaft “the east lode is from 24 feet in width on the 500-foot level to 17 feet on the 650-foot level and contains copper on both levels. The west lode was reached by crosscutting through 17 feet of trap rock. The west lode is about 17 feet wide horizontally on both levels and contains copper.”

[6]Ojibway Mining Co., Repts., 1909-1912.

[7]Lake Superior Mining Inst. Proc, vol. 17, p, 234, 1912.

Little information is available as to the character of the lode at the Cliff shaft. From an inspection of the dump the impression was gained that the lode is mainly of the cellular type, though some breccia is present. The diamond-drill hole at the shaft shows two flows, the bottom one 134 feet thick, with a 6-foot amygdaloid, and the top one 30 feet thick, with a 7-foot amygdaloid. In the main the lode seemed rather poorly oxidized. Feldspar phenocrysts are present bat rather sparingly. Most of the work was done on the lower amygdaloid, from which most of the material on the dump was probably derived.

At the Rhode Island mine 10 feet of breccia lode, almost a “conglomerate,” was noted by Lane. The thickness of the basal bed is 19 feet; the west flow is 86 feet thick, with 11 feet of red amygdaloid.

At the Franklin Jr. mine the Kearsarge amygdaloid was located,[8] and the cores show a little copper.[9] The thirty-second level crosscut showed enough copper on the footwall side of the lode to warrant further exploration, according to the report of the company. The explorations in the new Kearsarge shaft show three Kearsarge flows with cellular tops.

In the Delaware drill section the Kearsarge amygdaloid has been cut in several diamond-drill holes. In all it is a thin (3 to 4 feet), nonfragmental, poorly oxidized amygdaloid. Some of the holes cut “west” lodes also with thin, nonfragmental, poorly oxidized amygdaloids.

South of the main productive area the lode, so far as known, seems to be thinner and less fragmental than in the productive area. This change is apparent in the south end of the Centennial mine. Little is known of the character of the lode in the Calumet & Hecla, but farther south, in the La Salle mine, it is only locally fragmental and in general only moderately oxidized. The diamond-drill records show that the Kearsarge flow in La Salle ground consisted of three to five thin flows with amygdaloids. In the south shafts the development seems to have been on the upper amygdaloid of this series. The north shafts are evidently on the first amygdaloid above the Wolverine sandstone. In the Laurium ground the diamond-drill record indicates but one thick flow.

In the productive area of the Kearsarge lode the copper has practically all come from the first amygdaloid above the Wolverine sandstone.

From these notes it appears that nowhere outside of the main productive area have large areas of thick “fragmental lode” been discovered.

[8]Franklin Mining Co. Rept. for 1905, p. 12.

[9]Idem for 1916, p. 8.

STRUCTURE

ALLOUEZ ANTICLINE

The major structural feature of the productive part of the lode is the Allouez anticline. The axis of this arch passes near No. 1 Ahmeek shaft; the beds flatten out at the south near the Centennial shafts and at the north between Nos. 3 and 4 Mohawk. Within these limits the average divergence from a plane in the position of the Kearsarge bed outside this fold is about 5° for both limbs, or about 9 feet in 100 feet. The steepest dips are at the crest of the anticline, and if the dips continue down the lode at the same angle as at the surface, the anticline must gradually flatten, and at 10,000 feet down the dip it must nearly disappear. The anticline is much less pronounced in the higher beds of the series than it is toward the base.

FAULTS AND FISSURES

By far the most prominent series of fissures strike a little west of north and as a rule dip steeply eastward. Among these are the shatter zone, the Mohawkite, Mass, and Fulton fissures, and half a dozen fissures in the Mohawk mine. Fissures of this series are less abundant to the south but are present throughout the developed area.

There has been some movement on many of the fissures. The shatter zone passing through Ahmeek and Allouez has the greatest displacement. It is a belt 200 to 400 feet wide that contains many fissures. It has been traced through the Ahmeek and Allouez workings, and its persistence to the north and south is indicated by the low Allouez Gap, which doubtless has resulted from erosion of the weakened rocks of this zone. The displacement is about 100 feet, the lode to the north of the zone being that distance to the west of the portion to the south. Both the north and south boundaries of the zone are marked by strong red clay gouges; that to the north is the thicker, measuring from 6 inches to several feet. Associated with the north gouge is a strong prehnite-epidote-copper vein that has been greatly shattered, seemingly by the movement that produced the fissure.

The shatter zone that passes along the boundary between the North Ahmeek and Mohawk mines offsets the lode in the upper workings of the Mohawk, but this offset decreases with depth till in the North Ahmeek it is little more than the width of the lode. This shatter zone is narrower than the Ahmeek-Allouez zone but resembles it closely in other respects. It is considerably wider in the Mohawk than in the North Ahmeek. The fault south of No. 1 Gratiot offsets the lode about 50 feet to the west on the north side.

The other prominent fissures commonly show a little gouge, and in places there is some brecciation of the adjacent rock. Not uncommonly the fissure zone widens out to 2 to 3 feet.

Another set of fissures strikes approximately east, or nearly at right angles to the north-south fissures, and usually dip steeply south. None of these are prominent, and few can be traced for more than a few hundred feet. There are numerous fissures in the mines that do not seem to fall into any well-developed regional system, but they are commonly small and traceable for only short distances.

ALTERATION AND MINERALISATION

OXIDATION

Oxidation was the earliest alteration of the lode. The oxidation of the Kearsarge and other lodes is fully discussed in the general section of the report (p. 34). The fragmental portions of the Kearsarge lode are highly oxidized and unusually high in ferric oxide. The oxidation is believed to have taken place during the cooling of the lava, earlier than and quite independently of the deposition of copper.

ALTERATION ACCOMPANYING MINERALIZATION

The alteration that took place subsequent to the oxidation may not all have occurred at the same time, but to separate it clearly is not easy. Much of it seems to have been closely associated with the deposition of copper, but certain phases of the alteration seem to have been more widespread than the copper deposition and not necessarily closely tied to it. For example, red feldspar, though present nearly everywhere in the Kearsarge lode, is distinctly variable in amount. In La Salle North Kearsarge, North Ahmeek, and Mohawk ground it is rather abundant, but in South Ahmeek ground there is less. Epidote is also far more widely distributed in the lode than important copper deposits. It may be added that what is true of the Kearsarge lode is also true of other lodes. Some that have very little copper shows a more or less pronounced epidotization. This suggests that some of the changes may not have been due primarily to the copper-bearing solutions but probably to the general temperature conditions that accompanied the mineralization.

The mineralization that followed the oxidation of the lode bore a distinct relation to the compositions of the lode after oxidation. Thus epidote, a ferric silicate, is abundant in the more highly oxidized portion of the lode but is much less abundant in the “foot lode” that was less highly oxidized. Chlorite and pumpellyite, ferrous-ferric silicates, are characteristic of the less oxidized “foot lode” and also of the basal amygdaloid of the hanging-wall trap, though they are also present in the more highly oxidized portion of the lode.

The change from epidote to chlorite in passing from the Kearsarge lode to the basal amygdaloid of the overlying trap is very sharp. Areas of these rocks but a fraction of an inch apart show the characteristic mineralization of each. In the west lodes, which are much less oxidized than the main lode, pumpellyite is relatively abundant. Minerals that do not contain iron show no such control as indicated above. Thus, quartz and feldspar are distributed throughout the lode, and so is laumontite where present; in fact, so far as recognized, the control is confined to the iron minerals.

The most conspicuous and striking change that is closely associated with copper is a pronounced bleaching of the rock around the copper in the upper highly oxidized portion of the lode. In this portion the copper has replaced the rock in masses of diverse sizes, the largest weighing several hundred pounds. Surrounding the copper is an area of light-gray rock in which the hematite of the red lode has largely disappeared. Quartz, pumpellyite, epidote, calcite, and some of the feldspar of the rock are the most abundant minerals. The relation of the copper to these minerals indicates that it is later and that it continued to replace these minerals after they were formed. In the lower part of the lode, especially in the “foot lode,” where the rock is much less oxidized, bleaching is less pronounced, epidote decreases in amount, and chlorite becomes abundant. The copper has replaced the rock to a less extent and is more abundant as an amygdule filling.

YIELD

In general, the Kearsarge lode is richest near the hanging wall; the richest ore is not always, perhaps not usually, at the very top, but the first 3 to 5 feet is the richest part of the lode and grades downward into leaner rock. In the Wolverine mine the “foot lode” was not extensively mined in the earlier years, but it is said to have been in the last few years a rather large factor in the production. In the earlier years the rock mined averaged 25 to 30 pounds to the ton; in the last few years it has averaged 15 to 16 pounds, indicating that the “foot lode” is much lower in copper than the upper part, though some low-grade material from the top part has been mined at the same time. A similar but much less marked change occurred in the South Kearsarge when the “foot lode” began to be more extensively mined.

The copper derived from a given area of lode varies to a considerable extent with the thickness of the lode, though there are notable exceptions. For the larger mines on the Kearsarge as to which data are available, the following table shows the average calculated thickness of lode stoped, the average quantity of rock mined per square foot of lode area, and the average yield of copper.

Rock mined and copper produced per square foot of Kearsarge lode

Mine	Thickness of lode (feet)	Rock (tons per square foot)	Copper (pounds)	
			Per square foot	Per ton of rock
South Kearsarge	12. 6	1. 05	18. 8	17. 98
Allouez	10. 9	. 91	15. 23	16. 74
Ahmeek Nos. 1 and 2	10. 1	. 84	17. 26	22. 15
Ahmeek Nos. 3 and 4	9. 3	. 77		
Mohawk	9. 5	. 79	13. 8	17. 48
Wolverine	8. 69	--------	17. 19	23. 2
North Kearsarge	7. 64	--------	10. 4	15. 62
Centennial	6. 3	--------	7. 72	14. 6

The relatively large amount of unprofitable ground in the Wolverine, Centennial, and North Kearsarge make the figures for these mines less accurate.

There is a rather regular decrease in the average stoping width from the South Kearsarge mine northward to the Mohawk, the average in the latter mine being fully 3 feet less than that in the former. Except in the South Ahmeek (Nos. 1 and 2) there is also a decrease in the copper per square foot of lode. The Wolverine has the highest-grade rock, and in part of the mine the lode is as thick as in the South Kearsarge, so that this part probably has the highest yield per square foot of lode. The grade of rock in the Ahmeek has averaged distinctly higher than that in the South Kearsarge, but the average thickness stoped is 2 feet less, so that the average per square foot of lode is slightly less.

It appears that although the lode is mineralized from the Centennial to the Mohawk, two areas richer than the average have been developed. One includes the South Kearsarge and Wolverine with adjacent parts of the Centennial and North Kearsarge; the other includes the South Ahmeek, South Mohawk, and parts of the Allouez. There are also certain poor areas that in general correspond to the areas of thin and cellular lode already outlined and associated with the strong fissures and fissure zones. (See pl. 40.)

PROBABLE CAUSES OF RICH AND POOR GROUND

Three principal causes seem to have been operative in determining the richness of the ground—character of rock, structural relations, and relation to strong fissures. Of these the character of rock and relation to strong fissures are the more conspicuous.

CHARACTER OF ROCK

Within the productive portion of the Kearsarge lode the thin parts of the lode and those consisting of dense, trappy amygdaloid are consistently poor. In the larger areas where the lode is poor it is thin or tight and relatively impermeable. The richest ore has been formed in thick masses of strongly developed fragmental top. The thick parts of the lode are not all rich, nor are parts of apparently equal thickness similarly rich, but rich parts of the lode are always thick or loose and fragmental in texture. Outside of the main productive area there are, so far as available data indicate, no large areas of thick fragmental top, most of the outside exploration having disclosed only thin or cellular amygdaloid.

The parts of the lode that are above the average grade in the Ahmeek mine and the south end of the Mohawk are decidedly of the fragmental and well-oxidized type. The same is apparently true of the Wolverine-South Kearsarge shoot. In the North Kearsarge mine and in the upper levels of Gratiot No. 2 shaft there is some good-looking rock that carries only a fair quantity of copper. The lode in the north end of the Mohawk mine is prevailingly cellular to trappy, moderately thick, and moderately oxidized. It contains some very good ground, but much of it is only fair, and a considerable amount is poor. The same is true of the thin and trappy portions of the lode in the North Kearsarge, Wolverine, Allouez, and Seneca mines.

INFLUENCE OF STRUCTURE AND TEXTURE

The structural and textural features that had an influence on the movement of solutions may also have been an important factor in directing solutions to or from certain parts of the lode. The structural features are independent of the lode; the textural features form a part of the lode.

Structure.—The structural features that have affected the movement of solutions in the lode are folds, faults, and fissures.

The Allouez anticline is the most pronounced fold in the productive area of the lode. If the solutions were traveling upward through the lode, they would have a tendency to move toward and concentrate along the crest of the anticline, and, other things being equal, this should be relatively rich ground. Nos. 1 and 2 shafts in the Ahmeek mine are essentially on the crest of the anticline, and although the stoping width here is less than in some of the mines farther south, the grade of the rock averages higher than in any other mine except the Wolverine.

Faults that offset the lode by more than its thickness and that intersect it in a line whose course is not directly down the dip constitute barriers beneath which the solutions may be concentrated and thus produce rich shoots of ore. The shatter zone is the only fault on the Kearsarge lode that seems likely to have had such an influence, and the extent of its influence is not very clear. Some rich ground was found close under it in the Allouez mine, but to what extent this ground was due to the shatter zone can hardly be stated. The rich ground of Nos. 1 and 2 Ahmeek shafts is in an area of strong fissures, including the shatter zone and the Mohawkite and Mass fissures, but convincing evidence that these fissures were a factor in the enrichment of the lode in this area has not been found. Sulphides are present in small amounts in numerous places in the lode but are most abundant near the shatter zone.

The lode is crossed by many fissures, the most prominent of which strike west of north and dip steeply east. Many of these fissures contain copper as native metal, as arsenides, or as sulphides. The Mass fissure has been by far the most extensively developed, but copper is present at the crossing of the lode in many of the fissures.

The fissures vary considerably in the character of their mineralization. In the Mass fissure calcite is the most abundant gangue mineral, though quartz and epidote are locally abundant. In the Mohawkite fissure quartz is relatively plentiful. In the arsenide fissures in the north end of the Mohawk mine ankerite (iron-calcium-magnesium carbonate) is a very abundant constituent, and specularite was noted in small amount at one point. Even where the ankerite is the predominant gangue mineral in the arsenide fissures, the mineral most intimately associated with the arsenide is quartz.

In the Mass fissure there is a decided concentration of the copper at the crossing of the Kearsarge lode and for a few hundred feet above the crossing, beyond which it falls off rapidly, though copper is present as much as 1,100 feet from the lode. Few of the other fissures have been followed far enough away from the lode to show the relations clearly, but so far as the evidence goes it indicates a strong tendency for copper to be precipitated in and near the Kearsarge lode. This is shown in many of the small fissures, which contain masses of copper in the lode but little or no copper even a few feet away. A drift has been extended into the hanging wall on a fissure (Mohawk No. 4 shaft, 22d level south, near No. 5) for several hundred feet. For a short distance in the hanging wall there was considerable mass copper, but it seemed to decrease with distance from the Kearsarge lode, though the drift has not been extended far enough to demonstrate this conclusively.

The arsenide fissures, such as the Mohawkite, have been prospected but a few feet from the lode in the Ahmeek mine, and the influence of the lode on the precipitation of the arsenides is not known. The arsenide fissure near the north end of the Mohawk mine has been followed by drifts in the upper levels. The mineral seemed to occur at the crossing and for a short distance in the hanging wall, as on the Mass fissure. A number of the less prominent fissures, such as the Fulton and some unnamed fissures in the Ahmeek and Allouez mines, contain arsenical copper, and these seem to correspond in habit to those that carry copper, so that there appears to be a very close relation between the copper fissures and the arsenide fissures. A relation between copper in the fissures and in the lode is indicated by the presence of some arsenical copper in the lodes near the arsenide fissures. The fissures that contain arsenide are either strong themselves or are closely associated with strong fissures.

Texture.—The textural features within the lode that have been effective in diverting and converging the mineralizing solutions are the areas of relatively impermeable amygdaloid. The rock in these areas is by no means absolutely impermeable, but its permeability is sufficiently low to cause some of the solution that would naturally pass through it to move by easier channels through the areas of thicker and more permeable rock.

A long bar of thin or cellular lode extends from the Ahmeek to the South Kearsarge in the upper levels of the mines. In the lower levels of the Allouez there is another bar of thin lode that reaches the bottom of the mine and has not been completely outlined, but there is a suggestion that at deeper levels it may extend pretty nearly across the Allouez and into the North Kearsarge. Between these bars of thin lode is an area of fair to thick lode in the North Kearsarge that is partly pocketed by the thin lode. At the south end of the barrier is the thick lode of the South Kearsarge, which reaches the present surface.

It seems possible that these two bars of thin lode have together tended to divert the solutions that were rising along the anticline southward through the thick lode of the Wolverine and South Kearsarge and that such a convergence of the solutions has resulted in the Wolverine-South Kearsarge shoot. Much of the lode that lies between these two bars in the North Kearsarge mine is of good thickness and looks favorable, and copper is well distributed through it, but the masses are small, and little of the lode rock is above average tenor and a considerable part is below average. It seems possible that owing to the barrier above, which prevented free passage out, and to some extent to the barrier below, which diverted the solutions southward, there was not a normal flow of mineralizing solutions through this part of the lode and therefore, though favorable in character, it was not heavily mineralized.

The Wolverine-South Kearsarge area is favorable because it contains the thickest part of the lode, and probably also because the bars of thin lode have diverted solutions through it that would otherwise have passed toward the outcrop through ground farther north.

A somewhat similar condition is present in Gratiot No. 2 shaft. The upper levels of that shaft are in a moderately thick, favorable lode but show little copper. From the tenth to the fifteenth level near the Mohawk boundary the lode is of good character and from fair to rich in copper. Between these areas of favorable rock is a bar of thin lode showing in the shaft from the eighth to the twelfth level. This bar has apparently diverted the solutions that mineralized the favorable rock below it; and the favorable rock above the bar, so far as developed, is poor in copper.

INFLUENCE OF FISSURES ON THE LODE

The influence of fissures on adjacent parts of the lode is striking and very generally recognized by the operators. Except in a very few places the lode in the immediate vicinity of strong fissures is decidedly lower in copper than the average at greater distance.

Strong fissure zones are most abundant in the Ahmeek and Mohawk mines. In both the change in appearance of the rock near the fissures is well recognized. In the Mohawk two general types of lode rock are recognized—

”gray lode” and “brown lode.” The “gray lode” is most extensive in the north end of the mine and the “brown lode” in the south end, though “gray lode” is present near the fissures in the south end. In the Ahmeek mine dark or chloritic lode rock is present along the Mohawkite, Mass, and Fulton fissures. The change in the lode along these fissures is due to a chloritization and to some extent a sericitization of the lode rock. Alteration of the same type has resulted in the “gray lode” near the fissures in the Mohawk mine.

It seems to be a general rule that the portions of the lode adjacent to the strong fissures in the Ahmeek and Mohawk mines are relatively poor. What seems to be an exception was seen south of Mohawk No. 4 shaft, on the twenty-second level near No. 5 shaft, where a “mass” fissure cuts exceptionally thick and highly oxidized lode. Here the lode is said to be well mineralized and carried considerable mass copper. Apparently mass copper was not encountered in notable quantity on this fissure in the higher levels.

The shatter zone seems to be similar to the fissures, except that in this zone there has been more movement of the rock and thick gouge has resulted. The rocks of the shatter zone seem to have been altered like those near the fissures, but in addition there is strong laumontitization. The gouge, however, is decidedly red, and the rock near the gouge is commonly red also, giving to the shatter zone a distinctly red tone. This zone is everywhere poor in copper.

In the Ahmeek and Mohawk mines the copper in the lode near the arsenide fissures is arsenical. In the Mohawk arsenical copper was found in the “gray lode” 35 feet from an arsenide vein.

CONDITIONS FAVORABLE TO MINERALIZATION IN THE KNOWN PRODUCTIVE PORTION OF THE KEARSARGE LODE

Several conditions that are regarded as having been favorable to mineralization are present in the productive part of the lode that are not known to be present outside of the productive area, and there are others that should be considered possibly favorable.

The lode is of the fragmental type throughout the productive area. Outside of the productive area, so far as indicated by data now available, there are no large bodies of thick fragmental lode.

The lode has suffered an unusually high degree of oxidation throughout the productive area.

The productive area is on the Allouez anticlne, which may have been a factor in the convergence of the mineralizing solutions.

The north end of the productive area is crossed by a series of strong fissures. This is not regarded as among the favorable conditions, but it may be so.

In the same cross section as the central portion of the productive part of the lode but at a lower stratigraphic horizon is a body of intrusive felsite. This is another factor which is not regarded as essential but which may be favorable.

EFFECT OF DEPTH ON THE COPPER CONTENT OF THE LODE

The study of the Kearsarge lode has shown no evidence of leaching of copper near the surface and reprecipitation at greater depth. Where the lode is poor at the surface, as in parts of the Wolverine and North Kearsarge mines, the rock is impervious and unfavorable, and there is no indication that it was ever well mineralized. Where similar rock is encountered in the deeper workings, as in the lower part of the Allouez and in part of the North Ahmeek, the low copper content is encountered.

Where favorable lode rock reaches the outcrop, as in the south end of the Mohawk mine, it is well mineralized, and the same is true of favorable rock at greater depth.

If the mineralizing solutions in the main were traveling up the lode, the lode in general must continue permeable down to the connection with the source of the solutions, otherwise they would not have found their way to the level now developed. That mining will disclose areas of unfavorable rock and variation in the copper content at greater depth is to be expected from the known conditions in the developed areas. The encountering of an area of unfavorable rock should not be regarded as discouraging for the lode as a whole, though it may be so for an individual property. Poor ground, due both to character of rock and to the influence of fissures, is likely to be found here and there at greater depth as it has been to the present depth.

It is not intended to imply that a general decrease in the copper content of the Kearsarge lode will not be found at depth, but there is no reason to think that it will be other than a gradual falling off for the lode as a whole. So far as known, the causes that resulted in a decrease in the grade of the rock on the Calumet & Hecla conglomerate lode—namely, an increase in the thickness and extent of the lode with increased depth—will probably not affect the Kearsarge lode. The conditions are more likely to approach those of the Quincy lode, where a depth nearly as great as on the Calumet & Hecla conglomerate has been attained with no notable decrease in copper content.

MAYFLOWER-OLD COLONY MINE

The Mayflower-Old Colony Co. was formed by a consolidation of the two properties indicated in the name. The property covers the portion of the copper-bearing series extending from a horizon a short distance below the Wolverine sandstone to the Keweenaw fault. It lies east of the Calumet & Hecla (Centennial and South Kearsarge) and Mohawk (Wolverine) ground.

STRUCTURE

The rocks conform to the general strike and dip of the beds in this part of the range down to about the horizon of the “St. Louis” conglomerate, where the normal structure is interrupted by the Mayflower fault. This fault is apparently a branch of the Keweenaw fault, which it seems to join a short distance south of the Old Colony tunnel. The Keweenaw and Mayflower faults diverge from a point south of the Old Colony tunnel (see pl. 8) to a maximum known separation of about half a mile in the north end of the Mayflower-Old Colony property.

At the Old Colony tunnel the Mayflower fault is about 700 feet east of and several hundred feet stratigraphically below the “St. Louis” conglomerate. To the north the fault approaches the “St. Louis” conglomerate, and in the north end of the property near the surface it cuts out that conglomerate and some of the overlying “Big” trap. The dip of the fault is slightly steeper than that of the beds, and at depth the “St. Louis” conglomerate is present in the north end of the property, as indicated by diamond drilling. The continuation of this fault north of the area drilled can only be inferred. The “St. Louis” conglomerate crops out about half a mile north of the northern drill holes, and it is pretty certain that the fault lies east of the conglomerate and very probably connects with the area of felsite in that region (see pl. 8), with which, indeed, it may be associated in origin.

In the block between the Keweenaw and Mayflower faults the rocks are broken and displaced by minor faults of diverse attitude, but in general the beds are horizontal or have a gentle eastward dip—the reverse of that normal for the formation west of the faults. The block contains many beds of melaphyre and glomeroporphyrite, with some rather thick ophitic beds and two persistent beds of conglomerate. It is not positively known where these rocks belong in the general series, but there can be little doubt that they are higher in the series than the rocks adjacent on the opposite side of the Mayflower fault. Similar traps are present in the series above the “Big” trap, but in the nearest sections observed there are no conglomerates above the “Big” trap that correspond with those below the fault. There are, however, sedimentary beds in the series both to the south and north that might have developed into conglomerates. Rocks similar to the series of melaphyres and glomeroporphyrites immediately above the “Big” trap do not again appear till the Greenstone flow has been passed, and it seems more probable that the rocks in the fault block correspond to the series above the “Big” trap than to the series above the Greenstone flow.

DEVELOPMENTS

The earlier development of the Old Colony or southern portion of the property consisted of several shafts and a tunnel. The Old Colony tunnel starts near the Keweenaw fault and was driven across the series a distance of about 2,500 feet, or to the fourth flow above the “Big” trap. The No. 1 and No. 2 shafts were on amygdaloids about midway between the Kearsarge amygdaloid and the “Big” trap. No. 2 was on a bed a little higher in the series than No. 1.

No very clear record is available of the results of these earlier operations, though so far as known no copper was produced. On the dumps of No. 1 and No. 2 shafts there is some fragmental lode rock with a little copper. The pump shaft is on an amygdaloid a few hundred feet lower than No. 1 shaft. The North shaft, in the northern part of the Old Colony property, was in the area between the Keweenaw and Mayflower faults. The Haddy shaft opened two amygdaloids a little higher in the series than the No. 2 Old Colony shaft. The several operations apparently failed to open a lode that gave much encouragement.

About 1910 an extensive drilling campaign was undertaken by both the Mayflower and Old Colony companies to prospect the lower portion of the copper-bearing series on their properties. After this tract had been more intensively drilled than any other area in the Copper Range, the two companies were merged, and the present No. 1 shaft was sunk to a depth of 1,760 feet to prospect the Mayflower lode. The shaft starts in the “Big” trap, but the prospecting has been in the rocks below the Mayflower fault, on the 1,450 and 1,700 foot levels. The Mayflower amygdaloid occurs above two well-defined conglomerates, which have been a great help in working out the structure of this much-faulted block of ground. At the end of 1924 a crosscut was being run N. 70° W. from the seventeenth level, No. 1 shaft, to prospect above the “Big” trap at the horizon of the “St. Louis” amygdaloid.

ISLE ROYALE LODE

HISTORY AND PRODUCTION

Production from the Isle Royale lode (pl. 41) began in 1855. The present Isle Royale Copper Co. is a consolidation of several companies, including the old Isle Royale, Huron, Grand Portage, and Miners.

Production and dividends from Isle Royale and Arcadian lodes, 1855–1925

Mine	Period	Rock treated (tons)	Copper produced (pounds)		Dividends	
			Total	Per ton of rock	Total	Per pound of copper (cents)
Isle Royale lode:						
Grand Portage	1863–1884		3, 529, 622			
Huron	1855–1893		25, 309, 270			
Isle Royale	1853–1885		8, 818, 194			
Do	1901–1925	10, 469, 751	171, 718, 963	16. 39	2, 550, 000	1. 48
Shelden & Columbian	1864–1884		1, 463, 336			
			210, 839, 585		2, 550, 000	1. 21
Arcadian lode:						
Douglass	1860?–1877		169, 502			
Arcadian	1864–1902		3, 019, 206			
Concord	1866–1881		1, 595, 003			

EXTENT AND CORRELATION

What is now generally regarded as the Isle Royale amygdaloid has been known under several names. In the Isle Royale mine, from a point south of No. 7 shaft to a point north of No. 1, it is known as the Isle Royale lode. From a point north of No. 1 shaft to Portage Lake is what was known as the Grand Portage lode. Until recent years the identity of the Isle Royale and the "Grand Portage" lodes was not established. In the Isle Royale mine the part north of the fault was known as the West lode, but it is now evident that the two are faulted portions of the same bed, the Grand Portage or northern section being displaced westward about 175 feet, as is clearly shown in the mine workings.

North of Portage Lake the Arcadian lode, from its position relative to No. 8 conglomerate which lies below it, has been regarded as equivalent to the Isle Royale lode. The character of the lode material as seen on the Arcadian dumps shows a close similarity to the Isle Royale lode; the Arcadian, like the Isle Royale, is highly and coarsely brecciated and carries numerous inclusions in the lower part; its oxidation is comparable to that of the Isle Royale; and both sericitization and pumpellyitization are factors in its alteration. It was long supposed that the beds on opposite sides of Portage Lake were offset by a fault concealed by the lake. Marvine[10] assumed a horizontal throw of 720 feet, the north side being displaced westward. Hubbard,[11] however, has shown by the position and strike of No. 8 conglomerate at two points 15,000 feet apart on opposite sides of Portage Lake, that the horizontal displacement on this supposed fault could not exceed 275 feet. Furthermore, it is now known that the fault already mentioned as occurring north of the Isle Royale No. 1 shaft intervenes between the two positions used by Hubbard and accounts for 175 feet of the total, thus reducing to a maximum of 100 feet the displacement of a fault under Portage Lake. So small a displacement over so great a distance may be due simply to a slight bend in the strike of the formations.

[10]Marvine, A. R., Michigan Geol. Survey, vol. 1, pt. 2, p. 61, 1873.

Farther north the "St. Louis" lode is at about the same horizon, but neither this nor any other known lode north of the Arcadian bears close resemblance to the Isle Royale.

To the south a lode in the stratigraphic position of the Isle Royale has been opened in the Elm River (Contact) property near Twin Lakes, and also in the Winona mine, where it is known as the Winona lode and has a thick breccia top with pumpellyitic alteration like that of the Isle Royale. Identification still farther south is less certain; the Evergreen and succeeding lodes and the Forest ("Victoria") lode are at about the same distance above the supposed No. 8 conglomerate as the Isle Royale lode. These lodes are considered separately.

Thickness of Isle Royale flow

	Feet
Arcadian:	
Amygdaloid portion	27
Trap portion	117
	144
Isle Royale:	
Crosscut, sixth level north of No. 4 shaft	66
Diamond-drill hole No. 4, near No. 6 shaft	93
Diamond-drill hole No. 5, south of No. 7 shaft	81

CHARACTER OF LODE

The Isle Royale flow as represented at the Isle Royale mine is of the fragmental-top type so well illustrated elsewhere in the Baltic, Kearsarge, and Osceola lodes. The lode or top portion of the flow may in turn be separated into several phases or types that are easily recognized but that show gradation from one to another. These may be designated, from the top down, fragmental zone, banded amygdaloid, "vein trap," and foot-inclusion zone. The last forms the transition to the main trap portion of the flow. In addition, irregular small tongues or stringers from the overlying flow extend down in many places from a few inches to a few feet into the upper portion of the lode and are distinguishable only with some care from the lode proper.

[11]Hubbard, L. L., Michigan Geol. Survey, vol. 6, pt. 2, p. 108, 1898.

FRAGMENTAL ZONE

The fragmental portion of the lode consists of irregular fragments of amygdaloid and fine-grained trap ranging from small grains to tabular blocks several feet in greatest dimension. In form the fragments range from sharply angular through sub angular to fairly well rounded. In general, the larger fragments are more angular than a large proportion of the smaller fragments. The top portion of the fragmental zone is composed of fragments of a little smaller average size than the bottom portion. In any given section of the lode, however, there is a mingling of fragments of varying size. In texture the fragments may be very finely amygdular, or more coarsely amygdular with distinct "chilled" or finer-grained margins, or trappy and virtually uniform in character. The more traplike fragments are in general commoner near the base than near the top of the fragmental part of the lode.

As a rule the vesicles are filled with minerals, though they may be only partly filled, especially if epidote is the filling material. The spaces between the fragments likewise contain minerals. In general, the color of this mineral filling, whether in the interstices or as amygdules, contrasts plainly with the usual red color of the rock fragments themselves; but in many places near the overlying trap, especially where the lode is thin, the rock, although clearly brecciated, contains little mineral filling of contrasting color, and the lode has in consequence a dead, "burned" appearance, mottled with alternating small patches of brick-red and darker brown, dark gray, or dark green.

BANDED AMYGDALOID

Relatively short stretches of the lode contain, banded amygdaloid similar in general to what has been called "intermediate lode" in the Kearsarge but less abundant and persistent. This material may be overlain by the hanging-wall trap and grade below into the foot inclusion zone, or elsewhere banded amygdaloid a few feet thick may persist over considerable areas immediately below the fragmental zone. In other places large slabs of banded or cellular amygdaloid lie in the midst of the fragmental material. Most commonly the fragmental zone gives place to the foot inclusion zone without a distinct intervening layer of cellular rock.

FOOT INCLUSION ZONE

Directly below the fragmental zone, or the banded amygdaloid, is a brownish-gray rock of rather fine trappy texture, known in the mine as “foot trap.” It commonly contains somewhat indefinite patches or inclusions of amygdaloidal rock; the amygdules in these fragments consist usually of chlorite, though less commonly of calcite or some other light-colored mineral, with or without chloritic amygdules near the outer margins of the inclusion. Some inclusions are sharply angular, essentially like the amygdular fragments of the brecciated portion of the flow, but far more are rounded, in consequence of partial melting by the inclosing material, and in extreme cases of melting or resorption the position of the original inclusion is marked by an area containing amygdular cavities but possessing no recognizable boundaries. The inclusions range, in general, from an inch or less to 6 or 8 inches in diameter; a few reach 2 or 3 feet. They are most abundant and most conspicuous in the upper part of this zone and decrease in number and become more completely resorbed and smaller farther down. They cease to be abundant 10 to 12 feet below the upper limit of the zone. These amygdular inclusions are regarded as pieces from the fragmental zone sunk or dragged into the lower, still molten, and moving portion of the flow and partly remelted by it.

In contrast with the amygdules of these inclusions, the trappy rock of this zone contains amygdules of its own, but these are commonly sparsely distributed and noticeably large, as is usual in the lower portions of the lodes throughout the district.

VEIN TRAP

Slabs of trappy rock included in the fragmental zone are known as “vein trap.” In general this material shows no notable differences from that of the foot inclusion zone, though in places it exhibits a slightly chilled border. Some slabs have an under margin marked by notably elongated or “pipe” amygdules, and, as a rule, the large amygdules that occur sparsely in the foot inclusion zone are lacking. These slabs range from 1 foot to 4 or 5 feet in thickness and from a few feet to several scores of feet in extent. The smaller slabs may lie parallel to the walls of the lode or be tilted at any angle to them; the larger masses of necessity are essentially parallel to the walls. Fragmental material lies both above and below the slabs. These slabs of vein trap probably represent parts of the flow that solidified without brecciation just under the fragmental layer but were then broken by the continued movement of the flow and had fragmental material dragged or formed underneath them.

MAIN TRAP

The foot inclusion zone passes gradually into a monotonous trap rock, practically devoid of amygdules and of amygdular inclusions, which constitutes the main lower part of the Isle Royale flow; this trap is greener and less brown than the trap of the foot inclusion zone.

HANGING-WALL TRAP

The trap immediately overlying the Isle Royale flow is a dark greenish-gray and distinctly crystalline rock that commonly may be distinguished readily from the more brownish and finer-grained trap of the flow itself. Pipe amygdules in the trap just above the Isle Royale lode are present in places, but they are by no means so common or so characteristic as in the corresponding position above the Kearsarge lode. The hanging-wall flow above the Isle Royale lode ranges in thickness from 195 to 225 feet. At Winona the flow above the Winona lode is 810 feet thick.

The trap has invaded the top portion of the fragmental zone as small tongues and irregular stringers that range from less than an inch to a few inches or even a foot or more in width. These tongues and stringers are distinctly reddish, and in this respect as well as in their finer grain they differ notably from he main mass from which they branch; they are thus more like the Isle Royale trap, from which, however, they may be distinguished by their denser texture, their amygdules, and their red rather than brownish color. These invading tongues are not everywhere readily distinguishable from the fragmental material that they penetrate, for the two are not unlike in texture and are closely similar in color. Ordinarily, however, the tongues are slightly redder near their margins, and at their very edges they may be marked by a faint lighter-colored line apparently due to incipient bleaching or else to the deposition of a colorless mineral. These invasions are rarely of such regularity as to be mistaken for dikes; they penetrate irregularly into and ramify through the fragmental material, parts of which they may surround. Although irregular and variable in direction, their average attitude is likely to approximate right angles to the hanging-wall contact, and they gradually fork and pinch, so that most of them terminate less than 4 or 5 feet below the contact. They probably represent places where the relatively fluid melt of the overlying flow has locally broken through the chilled lower contact of that flow and thus found access into the loose and jumbled material of the fragmental zone.

DISTRIBUTION OF TYPES

The distribution of the several phases of the lode seems most unsystematic. Throughout the mine areas of thick fragmental rock are interspersed with areas of thin, denser fragmental rock, of banded amygdaloid, or of vein trap. The foot inclusion zone is everywhere present, though its thickness and the number of its inclusions may vary.

The areas of thick fragmental rock are very irregularly distributed; at many places where the fragmental material was piled above the general level of the flow surface it now bulges into the overlying trap. Where these bulges are pronounced there may be an apparent local change in the dip of the lode, the dip seeming to flatten on the up-dip side of these bulges and to steepen on the down-dip side. A similar local modification of the footwall dip is effected by abrupt reentrants of the thick fragmental rock into the basal trap, the footwall dip being steeper on the up-dip side and flatter on the down-dip side of these reentrants. On the other hand, where the fragmental material is notably thin, the hanging wall appears to bend in toward the footwall and the footwall to rise from its normal position. In these thin places the fragmental rock commonly loses something of its brecciated appearance, becoming more dense and massive, but it retains its red color, which chiefly serves to distinguish it from the rock of the footwall.

There is thus a tendency toward alternate divergence and convergence of hanging wall and footwall—that is, toward alternate thickening and thinning of the lode. But not every swing in one wall is accompanied by an opposite swing in the other wall. Moreover, the bulges into the hanging wall, which may measure as much as 10 or even 20 feet, are more extreme than the bulges into the footwall, which ordinarily do not exceed 5 to 8 feet. The bulges of fragmental material into the lower part of the lode may be more abrupt^ so that locally the boundary between the fragmental zone and the foot inclusion zone may be almost at right angles to the plane of the lode. The bulges into the hanging wall are marked by slopes which appear to have been, when the flow was in its original horizontal attitude, of less than 40° and which thus may have been limited to the angle of repose of loose fragments. Vein trap is naturally commonest where the fragmental layer is thick but is not present in all thick places.

The various kinds of lode rock are not only irregularly intermingled but occur in decidedly different proportions in different parts of the mine. In the workings of No. 4 and No. 5 shafts the fragmental zone is relatively thick and the areas of thin lode and banded lode are comparatively small. In the No. 7 shaft region, down to the 7th or bottom level, the lode is relatively thin, and areas of thick fragmental rock are small. The ground south of No. 6 shaft is intermediate in character between that of No. 5 and that of No. 7.

In the old Huron workings, especially about No. 6 and No. 8 Huron shafts, the lode averages thinner than in the neighborhood of Isle Royale shafts Nos. 4 and 5, and the alternations between thick and thin lode are numerous and abrupt, especially in the upper levels. At certain of the thicker places, especially south of No. 8 old Huron shaft, the lode is double through the presence of a relatively large mass of "vein trap" between two layers of fragmental rock. Here both the upper and the lower fragmental layers were ore-bearing, but as a rule only the upper layer was thoroughly explored by the Huron management.

South of No. 2 shaft, in the upper levels, the lode is of good thickness and grade, but in depth, down to the Grand Portage fault and especially northward to the limits of the workings beyond No. 1 shaft, thin lode predominates, though with numerous local exceptions. The Grand Portage or faulted portion of the lode has essentially the same character as the main section south of the fault, but the average thickness of the fragmental zone seems to be a little greater than around No. 1 and No. 2 shafts, on the main section of the lode.

The distribution throughout the mine of areas of thick and thin fragmental material interspersed with cellular rock and of areas of trappy material overlain and underlain by fragmental rock, though suggesting complicated and varied modes of origin, is believed to result from comparatively simple conditions of movement and solidification while the flow was in progress, as is discussed in connection with character of tops on page 31.

STRUCTURE

ISLE ROYALE SYNCLINE

Aside from the tilting of the entire series, the largest structural feature revealed in the mine is the Isle Royale syncline. This is a gentle fold which accounts for the curvature of the lode. Its axis is at about No. 4 shaft. The fact that the best ground centers about the axis suggests that the presence of the fold had something to do with the localization of the copper.

The dip of the lode at the north and south, as near No. 2 and No. 6 shafts, respectively, is steeper, about 56°, than near No. 4 and No. 5 shafts, where the dip is about 51°. If a similar difference in dip were maintained downward the fold would become less and less marked, and at a depth of about 10,000 feet down the lode from the outcrop it would disappear. Indeed, at the present deepest levels the curvature of the lode is notably less than at the surface, that is, the levels are straighter than those above. On the other hand, the beds higher in the series, exposed to the west as far as the Ashbed or Atlantic lode, retain the synclinal structure. As these higher beds where they reach the surface overlie (stratigraphically, or perpendicular to the bedding) deeper parts of the Isle Royale lode and therefore are likely to reflect the structure existing at depth on that lode, it would seem probable that the Isle Royale syncline persists downward for a long distance.

FAULTS

The only large fault recognized in the mine is the Grand Portage fault, encountered in the north end. It strikes N. 35°-60° E. and dips 60°-80° NW. The section north of the fault is the "West lode," known as the "Grand Portage lode" before its identity with the Isle Royale was established. Where each section of the lode meets the fault, it is bent or dragged around so as to point somewhat in the direction of the other section. This attitude confirms the conclusion as to the direction of displacement caused by the fault and strengthens the correlation of the two sections as parts of the same lode. The fault offsets the northern section of the lode about 175 feet toward the west, as measured on the level.

This is the distance at right angles to the lode, but the actual amount of displacement must have been greater, ranging from some 300 B feet to very much more, depending on the direction of the movement. On the assumption that the fault is an overthrust the Grand Portage section moved relatively upward and slightly to the southwest. If that is assumed as the true direction of displacement, then any point in the lode south of the fault would find its equivalent in the Grand Portage block some four or five levels higher up. But in any case, except that special one in which the displacement had been entirely in a horizontal direction, equivalent portions of the lode on opposite sides of the fault would not be at the same level. This relation may explain differences in the lode on the two sides of the fault on any given level.

The character of the Grand Portage fault varies from place to place. In the upper levels north of No. 1 shaft it is a clean-cut break, carrying from a few inches up to 2 feet of gouge and brecciated rock, with pronounced dragging of the lode but only minor fracturing parallel to the fault. Toward the bottom of No. 1 shaft, however, and in the workings north of No. 2 the fault is less definite and simple; it tends to fray into a series of fractures of somewhat variable dip and strike but conforming on the whole to the general direction of the fault; these fractures are more likely to carry veins of either light or dark colored calcite than to contain a notable amount of gouge.

Another fault of approximately the same strike and dip and with the same direction of displacement was observed from the eighth level of No. 4 shaft close to the old Huron workings to the sixteenth level south of No. 4, or beyond. Its horizontal displacement is not over 30 feet as measured on the levels. In character it resembles the Grand Portage fault, being well defined and only a few inches to a foot in width in the upper levels but breaking into branches that form a fractured zone in the deeper workings. It carries quartz, calcite, pumpellyite, copper, and chalcocite.

In contrast with these two faults, which appear to belong to the same series, there are other faults and fractures that strike nearly parallel to the lode but generally a little more to the north. More than half of these dip against the lode; the others dip with it, all at angles steeper than the inclination of the lode. The small divergence in strike between these fractures and the lode might permit considerable displacement along them to escape recognition, but so far as can be seen there is only slight displacement along any of these breaks and none whatever along many. They are rendered conspicuous chiefly by the vein minerals deposited in them, which consist mainly of laumontite, calcite, and quartz, in places with a little chalcocite or copper.

All these faults for which the direction of displacement is evident appear to be reverse faults—that is, the hanging-wall side of the fault has been raised relative to the footwall side. This is the same type of faulting as that shown by the Keweenaw fault. Diamond drilling has disclosed, according to Lane, several other faults between the Isle Royale lode and the Keweenaw fault and parallel to the Keweenaw; these he has interpreted as probably reverse faults also. It thus seems reasonable to assume that the hanging-wall block of the Keweenaw fault, up to and beyond the Isle Royale lode, suffered distortion at the time of the main faulting and had relatively subordinate sympathetic faults and fractures developed in it.

The faults carry minerals of the general period of copper deposition and thus are believed to have been formed before the mineralization.

FISSURES

Fissures are abundant in the mine and vary greatly in their attitude. Some of the larger ones are discussed above in connection with faulting. Most of the fissures can be grouped into a few systems. Those of one system strike N. 50°-65° E., and most of them dip southeast at rather steep angles, although some of them dip northwest. This system is best developed in the south end of the mine and is more sparsely represented in the north end. Another system strikes N. 25°-45° W. and has steep dips. It is represented in both the north and the south ends of the mine. A third series strikes nearly parallel to the lode and dips in the same direction as the lode but perhaps on the average a little more steeply. This system apparently changes strike with the main curvature of the lode and so keeps essentially parallel with the lode throughout the mine. A slight amount of displacement of reverse-fault direction can be seen along some of these fissures.

These fissures are present in the main trap under the lode, and some of them pass through into the hanging-wall trap where this is exposed by the workings. As a rule only the stronger fractures persist from the trap of the footwall into the fragmental zone, and many of these are deflected upon entering the lode to a course approximately parallel or more nearly parallel with it. In general, then, fissures are most common in a zone a few feet thick that occupies the basal portion of the lode and constitutes the main copper zone. In places this concentration of fissures near the base of the lode gives to it a distinct appearance of sheeting approximately parallel to the walls, as is well shown in many of the old stopes, where in the blasting the rock has broken clean along these joints. On this account, and because of the position of the best copper along the base of the lode, in contrast with most of the other amygdaloids in which the best ground is near the hanging wall, it is desirable to ascertain the nature and cause of this fracturing and its effect on copper localization.

Copper mineralization is often found to have terminated downward at a fracture plane essentially parallel to the lode, known by the miners as the “foot slip” and regarded as the boundary between the lode and the underlying “foot trap.” The readiness with which the blasting breaks to such a fracture plane would seem to indicate that sheeting nearly parallel to the lode is indeed a characteristic of the zone just at the bottom of the fragmental layer.

The assumption of this condition of sheeting along the foot of the lode must not be carried too far, however. For example, where the fissuring essentially parallel to the lode is best shown, two or three other systems of joints are likely to be well developed also, and the question arises whether, if there were occasion to carry the mining in a different direction, one of these other joint systems might not seem the prominent one to the miners and be as conspicuous after blasting as the "foot slip" is now. In the crosscuts from shafts to lode it can not be seen that fractures or joints parallel to the lode are notably more common or stronger than those in other planes, and when the lode is reached it is not commonly marked by a conspicuous concentration of fracture planes parallel to it. Where the lode pinches and the footwall rises perceptibly from its normal position the "foot slip" tends to swing with the footwall, but it is less conspicuous where the footwall is high and the lode is thin than it is where it lies farther down from the hanging wall under a thick fragmental zone. The change in direction of the slip is also less extreme than that of the bottom of the fragmental lode. The slip is therefore deeper in the foot inclusion zone where passing over the upward bulges of the footwall than where the lode is thick, for there it is either close to or actually within the fragmental part of the lode.

The relative importance of the fractures that are approximately parallel to the lode as contrasted with fractures of other directions is not very definitely known. Their effect, however, in guiding and in limiting the flow of mineralizing solutions to the horizon close to the footwall can not be overlooked. It is not unreasonable to suppose that fissuring along the base of the lode and especially in a plane about parallel to the lode may be noticeable in the Isle Royale mine because of proximity to the Keweenaw fault to which this fissuring may be related. Another possible cause of the fracturing parallel to the lode is slipping of the beds when the Isle Royale syncline was formed.

Altogether, the origin and the importance of the foot slip at the Isle Royale mine are not at all clearly understood.

Many of the Assures are mineralized; the details are given under the next heading.

ROCK ALTERATION AND ORE DEPOSITION

The effects of two distinct periods of alteration can be recognized in the lode—one earlier than copper deposition and independent of it, the other believed to be closely associated with the formation of the ore.

FIRST PERIOD

Oxidation was the earliest alteration to affect the lode. This change probably took place before the lode was buried by the overlying flow. All of the fragmental part of the lode was decidedly oxidized and reddened, apparently about the same degree throughout its thickness. This porous material was apparently rather strongly affected by oxidation, even where overlain by a layer of "vein" trap. The cellular amygdaloid and the denser material that characterizes places where the lode is thin were also oxidized and reddened though to a less intense degree, and the oxidation and reddening extended with further decrease of intensity into the trap of the foot inclusion zone. In general, the fragmental portion of the lode has been more highly oxidized than the nonfragmental portion, but the fragments in the foot inclusion zone rarely show more oxidation than the surrounding trap.

The tongues of overlying trap that extend into the lode, as well as the bottom portion of the main hanging wall flow for a few inches above the lode are red and oxidized, in distinct contrast to the main portion of the mass. This oxidation may have been accomplished at the time of or shortly after the outpouring of the hanging-wall trap by means of the oxygen included in the porous lode on which it was spread. Although the oxidation of the main lode undoubtedly produced a notable change in color of the rock, through the development of hematite, the texture of the rock was unaffected, and feldspar, the chief constituent, was not altered.

SECOND PERIOD

The second period of alteration came long after the surrounding rocks had been formed, and probably after the lode had been tilted into approximately its present position. In contrast with the early alteration, a main feature of which was the conversion of ferrous iron to ferric, the alteration of the second period was complex and more intense, causing in many places a profound change in both appearance and character of the rock. Embraced in this composite alteration were the successive but somewhat overlapping developments of epidote, pumpellyite, quartz, sericite, calcite, metallic copper, and copper sulphides and arsenides, as well as several other minerals of less common or less abundant occurrence. This second period itself seems divisible into at least two and possibly three stages—an early stage intimately connected with the deposition of most of the metallic copper and producing epidote, pumpellyite, quartz, and calcite; a later stage subsequent to the deposition of most of the copper and characterized by the development of sericite with quartz, calcite, anhydrite, gypsum, and a little barite; and a final stage or else the concluding phase of the second, in which the minerals of the sericite stage occur along with copper sulphides and arsenides or arsenical copper, chiefly in veinlets through the lode.

The stage of copper deposition is marked by the production of a greenish or grayish rock, a result of the quartz-pumpellyite type of bleaching, in which pumpellyite is the most prominent mineral produced, with less abundant quartz, calcite, and epidote. A little prehnite, alkali feldspar, or laumontite may be present here and there. This greenish rock, dense and usually harder than the unbleached red breccia, is the characteristic associate of most of the metallic copper of the lode. It may occur in patches and streaks or may persist in long stretches of the lode, but it is generally confined to a layer embracing the lower part of the fragmental zone and the uppermost part of the foot inclusion zone; and it is from this layer that most of the copper is obtained in the mine. Little copper occurs in this layer that is not inclosed in the green, pumpellyitized rock, but there may be considerable masses of the green rock that contain little or no copper. As a rule, however, copper and | the bleached rock are close companions.

This green copper-bearing layer coincides closely with the zone of fracturing along the footwall described above under "Fissures." Many of the fissures either carry copper or are marked by especially pronounced pumpellyitic alteration along them. It may be that the concentration of copper and the accompanying bleaching was localized near the base of the lode by reason of this belt of fracturing, which added to the normal permeability of the fragmental part of the lode.

In places in this pumpellyitic zone the minerals and the texture of the original rock are entirely destroyed. Such alteration with attendant copper deposition is scanty in the thin parts of the lode, where there is little breccia, and is strongest where well-marked little altered fragmental rock lies above the pumpellyite zone.

On the under side, where the mineralized zone is in contact with the trap of the foot inclusion zone, the bleached rock is likely to terminate abruptly and in places is bounded by a break or fracture that separates it sharply from the darker rock underneath. It is probable that this green rock is formed mainly by alteration of the breccia and to a less extent by alteration of nonfragmental amygdaloid or of trap. At many places residual traces of the fragmental structure can be seen in the green rock, and it fades out gradually upward to typical red fragmental amygdaloid; in the main the alteration has obliterated the breccia structure, so that the part derived from breccia and that derived from the underlying trap are indistinguishable.

In places this pumpellyitic zone and the accompanying copper extend above their usual upper limit into the main fragmental portion of the lode, even to the hanging wall and rarely for a few inches into the overlying trap. In such places the alteration is less, the bleaching or removal of the red color and replacement by green not so marked, the destruction of the brecciated structure less thorough, and the amount of copper smaller than in the principal zone. These upward extensions of the copper-pumpellyite zone are generally in places where the lode is widest and the fragmental layer thickest—in short, probably places of greater than average permeability. In some of the old Huron workings, where a tendency toward double lode is to be seen, this bleaching is present in both hanging-wall and footwall portions, though it is not very intense in either.

Sericite is the most characteristic or distinctive mineral of the later stage of rock alteration. It is very abundant in some of the red fragmental parts of the lode, but its distribution is irregular, contrasting in this respect with the pervasive distribution of the pulverulent hematite that gives the red color to the breccia. In parts of the Isle Royale mine the breccia is well sericitized, as in the upper and intermediate levels of No. 6 shaft and in parts of No. 7 shaft and of the Grand Portage lode. In other parts of the mine, as In No. 2, No. 4, and No. 5 shafts, the sericitization was much less intense. The mineral occurs chiefly as a cement to the fragments, formed in part by filling of interfragment spaces and in part by replacement of the smaller fragments that lay between the larger ones. In many places where sericite was deposited, rock solution went on more rapidly than mineral deposition, the result being to produce a vuggy texture in the brecciated material. This is shown particularly well in the lower levels of No. 2 shaft, where pumpellyite and later sericite have replaced the breccia/leaving vugs that are now lined with crystals of calcite and quartz. Where present abundantly the sericite may be identified by its softness and rather greasy feel, also by its light color, ranging from white to pinkish or pale green, which contrasts with the strong red color of the breccia fragments cemented by it. In smaller quantity also it has partly replaced the larger fragments, but generally this replacement was not so extensive as to destroy either the texture or the red color of the fragments.

By deposition chiefly in the spaces between the fragments, the sericite appears to have luted or plugged up the breccia and thus to have decreased the permeability of those portions of the lode in which it is plentiful. Because of its soft and somewhat plastic character, the sericite would probably be more effectual in this respect than quartz, calcite, or the other brittle minerals that were deposited in similar relation to the breccia fragments.

It was at first thought that the deposition of the sericite with its plugging effect had taken place in the highly brecciated portion of the lode because that was the most permeable, before the pumpellyite-quartz-copper mineralization. Subsequent study, especially with the microscope, shows that this conclusion was ill founded. Nearly or quite all the sericite is found to be younger than the pumpellyite and to have replaced it in part. It is thus necessary to conclude that the solutions from which pumpellyite and metallic copper (and accompanying minerals) were deposited entered the lode before the fragmental portion was sealed up by sericite, that they therefore chose the zone near the base not by necessity but by preference, and consequently that this zone, because a site of fracturing, was actually more permeable at the outset than the highly fragmental but less fissured material overlying it. At places where the fragmental stuff was especially permeable, however—and apparently this is where it was thickest—some copper and zoisite did find their way up into it toward the hanging wall. Later, when the sericite-forming solutions came along, they had to content themselves with the main mass of the breccia, which was then the most permeable material available; they were excluded from the fractured zone near the base, which had already been occupied by copper and pumpellyite; they attacked the margins of the pumpellyite zone but were unable to penetrate far into it; and they gained little access to those thick places in the fragmental lode where copper and pumpellyite had been formed.

In much of the best ground in the mine, especially near the No. 4 and No. 5 shafts, calcite, accompanied by more or less quartz and by smaller amounts of prehnite, strongly predominates over sericite as the cementing material of the fragmental zone. In certain areas, moreover, notably on the fourteenth level south and nineteenth level north of No. 5 shaft, on the twenty-sixth and twenty-seventh-levels of No. 2 shaft, and on the fifteenth level at the south end of the Grand Portage section of the lode, anhydrite, with or without gypsum, occurs in a similar cementing relation to the breccia, locally forming patches several inches across. Scattered here and there through the lode also is a very little barite. The possible significance of these sulphate minerals is considered on page 136 in connection with the general hypothesis that the metallic copper was deposited as a result of the oxidation of copper sulphide solutions by hematite.

Copper sulphides and arsenical copper, accompanied by calcite, sericite, quartz, chlorite, and specular hematite, occur in numerous veinlets that cut the lode. Possibly contemporaneous with these are the copper arsenides that have been found on the twelfth level at the very north end of the Grand Portage section. These occur in fragmental material near but not actually in veinlets. The arsenide patches are bordered by rock that shows bleaching of the iron-removal type and that under the microscope is found to contain sericite in addition to the usual quartz, epidote, calcite, and laumontite.

In general the sulphide veinlets are narrow, being rarely more than 3 inches in width and commonly much less. In some, as one on the fourteenth level north of No. 5 shaft, the chalcocite occurs in short lenticular masses from which specimens weighing a pound or two may be collected. The gangue constitutes the chief filling or replacing material of the vein, so that it is frequently necessary to search carefully before finding the sulphide which the gangue minerals suggest is present. The wall rock of these veinlets is chloritized, sericitized, and calcitized. For a width of an inch or two the red wall rock may be bleached by the bodily removal of the iron and replacement by sericite and calcite; or the immediate walls may be dark green, owing to the removal of the ferric iron and the development of chlorite. In the vein proper calcite and quartz are the chief minerals, although ankerite, a carbonate of lime, magnesium, and ferrous iron, is also common. Where ankerite forms the gangue, both bornite and chalcopyrite may be very sparingly developed and specular hematite, magnetite, and metallic copper are also to be found. The central part of the vein may carry massive sulphide, which has replaced the carbonate.

As a rule the chalcocite is confined to the veins, but in the Grand Portage section as well as on the second and third levels north of No. 7 shaft it has been found sparingly developed within the sericitized lode. The distribution of arsenides and arsenical copper has not been studied in detail. At one place arsenical copper, domeykite, and whitneyite are associated with chalcocite; the age relations are not clear, but there is a suggestion that the arsenides preceded the sulphide. Arsenical copper has been found in highly sericitized fragmental rock; there may be in this mine a relation between arsenic and sericite, such as is shown by the sericitic alteration along the Mohawkite fissure in the Ahmeek mine, but the Isle Royale sericite is by no means invariably associated with arsenide or arsenical copper.

CHEMISTRY OF ORE DEPOSITION

The chemical changes that accompanied the deposition of copper in the Isle Royale lode appear to have tended in the same general directions as in the other important amygdaloids. In the main, the red lode rock seems to have been favored for replacement by copper. The rock alteration attending the precipitation of copper has been relatively profound. There has been a notable decrease in total Iron and a reduction of ferric to ferrous iron. As compared with the rock alteration accompanying the deposition of copper in the Kearsarge lode, there has been less removal of the iron, and more of what remains has been converted from the ferric to the ferrous condition; there has also been more deposition of quartz. The physical result is seen in the difference between the Isle Royale type and the Kearsarge type of bleaching.

Potash was a notable constituent of the solutions, as indicated by the abundant serlcite and the smaller amount of orthoclase feldspar, the former more and the latter less plentiful than in the Kearsarge and Osceola lodes.

Sulphides are more abundant in this lode than in the Kearsarge and Osceola lodes and indicate that in the later stages of the ore-depositing period, when subordinate open fractures were followed by the solutions, sulphur compounds were the stable form for copper deposition. It is not clear why hematite was destroyed on a large scale at the time when most of the copper was deposited and was later precipitated in minor amounts along with chalcocite. Arsenic as arsenical copper and arsenides may, like the sulphides, be products of the later stages of the period of mineralization, but the evidence on this point is meager and inconclusive.

Throughout the second period of mineralization as described above, various rock elements were taken into solution as the rock was attacked. The deposition of copper that bodily replaced the rock would also naturally force into solution such rock constituents as calcium, sodium, aluminum, and silica. It seems altogether probable that the gangue minerals formed by the mineralization, such as quartz, epidote, pumpellyite, serlcite, calcite, and laumontite, represent in the main recombinations of these rock constituents in forms that were stable at the successive stages of the mineralizing period.

ARCADIAN LODE

The Arcadian lode (pl. 42) was first opened by the Arcadian and Concord companies, which produced a small amount of copper. The most extensive developments were made by the Arcadian Copper Co. within a period of a few years, beginning about 1898. The lode was opened for about 8,000 feet along the strike by five shafts. North and south of this developed area are shallow shafts. The principal shafts from north to south are No 4, opened to the sixth level; No. 3, to the seventh level; No, 2, to the eighth level; No. 1, to the fifth level; and shaft A, to the ninth level. The most extensive stoping was done from No. 2 shaft, near the center of the developed area, and from shaft A, at the south end of the developed area. From 1899 to 1902 the Arcadian Copper Co. produced 2,950,000 pounds of copper. There is no available record of the grade of the ore, but it was not sufficiently high to justify continued mining of the lode.

The Arcadian lode is a few hundred feet above No. 8 conglomerate and is believed to be the northward extension of the Isle Royale (“Grand Portage”) lode. It was said to average about 13 feet in thickness. The material on the dump Indicates that the lode is well oxidized, and that, like the Isle Royale, it is strongly fragmental. The mineralization appears to be in general similar to that of the Isle Royale, though there is considerable feldspar in the Arcadian lode and little of the sericite that is locally abundant in the Isle Royale lode.

NEW ARCADIAN LODE

The New Arcadian lode is a short distance above No. 8 conglomerate and below the Arcadian lode. It has been developed by the Arcadian Consolidated Copper Co. through the New Arcadian and New Baltic shafts. From the New Arcadian shaft the lode has been opened along the strike for a minimum distance of about 2,500 feet on the 600-foot level, and the shaft goes down to the 1,850-foot level. From the New Baltic shaft it has been opened for about 1,500 feet along the strike and down to the 1,250-foot level; the most work has been done on the 950-foot, 1,100-foot, and 1,250-foot levels.

The New Arcadian lode is In general of the fragmental type, but stretches of fragmental rock alternate with stretches of cellular rock. The fragmental areas show encouraging mineralization, which is mainly of the quartz-pumpellyite-epidote type with some fairly coarse copper. Areas of cellular amygdaloid in this, as in other lodes, are characteristically poor.

No heavy faulting of the lode has been recognized, but there are some faults of small throw that offset the lode and have caused some difficulty in following it. To the present time (1925) there has been only a little test stoping and no production on a commercial scale. In 1915, according to the annual report of the company, 3,845 tons of rock yielded 79,209 pounds of copper, or an average of 20.62 pounds to the ton. In 1916, 1,391 tons of rock yielded 32,307 pounds, or 23.23 pounds to the ton. In 1917, 4,900 tons of rock yielded 53,278 pounds, or 10.87 pounds to the ton. The average for the three years was 16.3 pounds to the ton.

WINONA LODE

PRODUCTION AND CHARACTER

The main output from the Winona lode (pl. 42) has been derived from the Winona mine, which includes the King Philip mine. The lode was opened by old Indian pits and therefore discovered early. Operations by white men began about 1864, and a little copper was produced in succeeding years. In the earlier part of the productive period the recovery was not very high, because much of the copper is in rather fine particles. From 1902 to 1907 about 3,350,000 pounds of copper was produced. The mine was then idle till 1911, when the company was reorganized as the Winona Copper Co., and it was then active till 1920, when operations were suspended except for a little development work. Its total recorded production, from 1902 to 1920 is 1,262,678 tons of rock, yielding 17,684,234 pounds of copper—an average of 14 pounds to the ton.

The Winona lode is about 400 feet above No. 8 conglomerate, at the general horizon of the Isle Royale lode.

On the Winona property the Winona lode is developed by six shafts—from north to south Nos. 1 to 4 Winona and Nos. 1 and 2 King Philip. Development has been carried for about 9,000 feet along the lode.

The northern part of the developed portion of the lode crops out just at the base of a prominent bluff. On this outcrop the Indians dug shallow pits, and it was eventually opened by the northern Winona shafts. The southern part of the developed portion of the lode, which is opened by the southern Winona shafts and the King Philip shafts, was covered by glacial drift.

The writers did not examine the mine. The following description is made up from the mine maps, from examination of the dump, and from descriptions by Messrs. T. S. Woods and E. R. Seeber.

The lode, which is of the fragmental type and fairly well oxidized, appears to be very irregular, changing from thick to thin within short distances. There is a persistent “slide” or gouge zone a few feet above the lode—Mr. Seeber says about 14 feet. In places the lode extends to this “slide.”

The mineralization was of the same general type as that of the other lodes. Pumpellyite, quartz, epidote, and calcite are plentiful. Prehnite, laumontite, and probably other minerals are present. The copper is associated with quartz and pumpellyite.

As indicated by present developments, the ore lies in a flat southward-dipping shoot (see pl. 42) that crops out near Winona No. 2 shaft. The northern Winona shafts seem to pass through the shoot, but in the King Philip shafts it is several hundred feet below the surface. The ore-bearing ground is apparently made up of a series of small nearly parallel shoots, interspersed with poor streaks. Even the smaller shoots contain areas in which the lode is thick and relatively high in copper and areas in which the lode is thin and poor. Where the lode extends to the hanging-wall slip it is said to be thick and rich.

The Winona lode in many ways resembles the Isle Royale lode with which it is commonly correlated. So far as learned, however, it does not show the tendency for the ore to form near the footwall, which is so persistent and unusual a feature of the Isle Royale lode.

WYANDOT MINE

The Winona lode was opened at the Wyandot mine by a shaft to the 1,000-foot level, from which short drifts were run. The lode was reported as carrying some copper, but operations in this mine were soon discontinued.

ELM RIVER MINE

The Elm River Copper Co. opened a lode at the general horizon of the Winona by a shaft to the 500-foot level, where drifts were extended for about 1,000 feet. The lode was also opened on the first level for a few hundred feet. The results were apparently not very encouraging. At No. 6 shaft the lode was entered by a crosscut at a depth of about 250 feet and was followed for about 700 feet.

CHEROKEE MINE

The Cherokee Copper Co. opened a lode that is farther from No. 8 conglomerate and possibly stratigraphically higher than the Winona lode. A shaft was sunk to the fourth level and short drifts carried on each level. It was reported that some stretches of commercial ground were opened. There is a fault south of the shaft (see pl. 12) that displaces the rocks on the south about 500 feet to the east.

WYANDOT NO. 8 LODE

The Wyandot Copper Co. opened a lode in a crosscut from the 700-foot level, No. 11 shaft, about 1,100 feet horizontally (950 feet stratigraphically) below the hanging wall of No. 8 conglomerate. The lode was opened on this level and by a winze to the 800, 900, and 1,000 foot levels, on each of which drifts were carried. The lode is fragmental in character, and the results were reported as somewhat encouraging. A test shipment of 1,605 tons of rock made in 1917 yielded 12.54 pounds of copper to the ton.

EVERGREEN AND SUCCEEDING LODES

All the mines on the Evergreen and succeeding lodes were Idle at the time the region was examined, and only very meager observations underground were made at the Mass and Adventure mines.

OCCURRENCE

From the Lake mine at the north to the Victoria mine at the south there have been rather extensive developments on a series of lodes whose base is about 400 to 500 feet above No. 8 conglomerate and which extends through a thickness of about 500 feet of flows. This series is at the general horizon of the Winona and Isle Royale beds, to the north, and of the Forest ("Victoria") lode, to the south. The correlation of individual flows from one development to another is probably somewhat uncertain, but in each of the openings in the Lake, South Lake, Adventure, Mass, and Michigan mines there are several lodes that carry sufficient copper to have encouraged extensive development, and a substantial amount of copper has been produced from the series as a whole.

From higher to lower horizons the lodes are the Knowlton, Merchant, Mass, North Butler, Butler, South Butler, Ogima, and Evergreen, with other amygdaloids present in places. (See pls. 43-46.) The position of these lodes is shown in Plate 13. The lodes that have been most developed and most productive are the Butler, Evergreen, and Knowlton. The Butler lode has yielded the largest amount, but the Evergreen and Knowlton lodes have made a considerable output.

PRODUCTION

The records of production from the several lodes of the series have not usually been kept separate by the mining companies, but the total for the series is essentially the production of the companies mentioned below, with the exception of the production from the Minesota fissure and the Calico lode by mines that have become a part of the present Mohawk Mining Co. (Michigan mine) and from the Lake lode by the Lake Mining Co., which is not here included with the group.

Production from Evergreen and succeeding lodes to end of 1923

Mine	Period	Rock treated (tons)	Copper produced (pounds)	
			Total	Per ton
Lake	1909–1923	--------	[a] Small.	--------
South Lake	1915–1923	80, 075	1, 042, 211	13. 02
Adventure	1851–1923	--------	10, 783, 889	--------
Mass	--------	--------	50, 616, 877	--------
Michigan	1916–1920	--------	[b] 4, 065, 175	--------
		--------	66, 508, 152	--------

[a] Does not include production from the Lake lode.
[b] Estimated; does not include production from the Minesota fissure and Calico lode.

CHARACTER OF FLOWS

The flows of the Evergreen and succeeding lodes are intermediate in composition, falling toward the andesite end of the basaltic series. Texturally they are chiefly melaphyres and glomeroporphyrites, but ophitic texture occurs in some of the thicker flows.

STRUCTURE

Next to the general tilting of the beds and the Keweenaw fault the largest structural feature affecting this series of beds is the pronounced anticline with its crest at Mass. This fold extends southward nearly to Flintsteel River and northward to the Lake mine. Like the Baltic anticline, it does not show a gradual change in strike around the fold but a very sharp change at Mass City of about 35°.

The Lake mine syncline extends into this region, and this series of beds are involved in that fold, but the correlation of the individual beds in the Lake mine basin with the normally dipping beds to the north is somewhat uncertain, and the lodes have therefore been considered separately. There are many fissures and faults with small throw on the Mass anticline, as is usual where the rocks have been folded to that extent. The opportunity for observing these fissures has been too meager to warrant any generalizations regarding them. It may be noted, however, that many of them are probably tension fissures resulting from the folding, though some are essentially strike fissures that dip in an opposite direction to the lode. All the fissures noted are mineralized and were evidently formed before the period of mineralization, though there has been movement on some of them since mineralization.

CHARACTER OF AMYGDALOIDS

Wherever seen the amygdaloids of this series of flows are fragmental to some degree. Very commonly the fragmental material is rather coarse and trappy. Like all other fragmental amygdaloids these differ greatly in different places, but characteristically areas in which the lode is moderately thick and fragmental alternate with areas in which it is thin and cellular or trappy and fragmental. The relative extent of these areas varies from place to place.

Some of the lodes, especially parts of the Evergreen lode opened in the Mass mine, show locally a distinct tendency to pass into amygdaloid of the coalescing type, though this tendency was not seen to persist over very large areas.

MINERALIZATION

The result of mineralization in all the lodes of the series is similar. The abundant minerals are quartz, feldspar, pumpellyite, chlorite, calcite, and epidote. Red feldspar is usually abundant in all the lodes. The less abundant minerals are prehnite, datolite, and laumontite. Zeolites other than laumontite were not noted though possibly present. Anhydrite was found on the dump at the Mass mine, but this mineral seems to be relatively rare in these as in other lodes.

Copper in small and large masses is irregularly distributed through the lode. In the Evergreen lode, in the Mass mine at least, much of the copper is present in masses—in fact a rather large percentage of the copper in all the lodes is coarse.

ROCK ALTERATION

The quartz-pumpellyite rock is the characteristic product of rock alteration associated with the copper, though there has been much replacement of rock by red feldspar and less by chlorite and epidote.

RELATION OF MINERALIZATION TO CHARACTER OF LODE

A close relation between character of lode and mineralization is evident wherever the lodes have been examined. Rich ground is wholly confined to fragmental parts of the lode, and the areas of good ground usually coincide with areas in which the lode is also relatively thick. The thin, cellular, and trappy parts of the lode are consistently poor. There is apparently some tendency for the favorable rock to form belts or “shoots,” but observation in the mines has been too scanty to make this certain.

BUTLER LODE

MASS MINE

The Butler lode (pl. 45) has been the most productive of the lodes of this series and has been most extensively developed in the Mass mine, where it has been opened for about 5,000 feet along the strike and rather extensively to the thirteenth level. Large areas have been stoped in the ground adjacent to shaft C. Near shaft B and, more especially, near shaft A the stoping has not been as continuous, and presumably the ground is less regularly mineralized.

Lithologic character.—Where examined, as it has been over small areas only, the lode is generally fragmental but largely of rather coarse trappy character. As in most other fragmental lodes, areas of definitely fragmental rock are interspersed with areas of thin trappy or cellular rock. Mr. E. W. Walker, the superintendent, states that in places the lode was unusually wide and was mineralized near the footwall and hanging wall but barren in the middle. In such places two stopes were carried.

Structure.—The main structural feature of the lode in this mine is a series of mineralized fissures. Locally these may show slight displacement, but they rarely offset the lode as much as its width. A “crossing” near shaft A is said to displace the lode along a brecciated zone. No mapping of the fissures has been carried over the area, but there is one series striking northeast and one northwest. There are also fissures striking approximately with the lode, some of which dip with the lode and others across the lode at a high angle. All the fissures contain essentially the same minerals as the lode and were evidently formed before the mineralization, though there has been movement on some of them since mineralization. According to Mr. Walker, no close relation between fissuring and mineralization of the lode has been recognized, though the fissures have evidently rendered the lode more permeable.

Mineralization.—The most abundant minerals of the lode are quartz, calcite, pumpellyite, epidote, and feldspar. Datolite is not uncommon but apparently not abundant. The pumpellyite type of bleaching was the characteristic alteration associated with the deposition of copper. The fine copper of the stamp rock is said to be more evenly distributed in this lode than in the Evergreen lode. That there is considerable coarse copper, however, is indicated by the fact that mass copper constituted about 26 per cent of the total mine production. In the present stage of development, no definite trend of ore shoots has been recognized on a large scale. Minor shoots of good and poor ground are recognized.

Yield.—During the late years of mining by the Mass Consolidated Mining Co. the yield was about half a ton of stamp rock per square foot of lode. As about 50 per cent of the rock was discarded underground, about a ton of rock per square foot of lode was broken, or an average thickness of around 12 feet. The rock milled yielded 15 to 17 pounds of copper to the ton.

ADVENTURE MINE

In the Adventure mine the Butler lode has been opened for about 2,500 feet along the strike and down to the eighth level, but only relatively small areas have been stoped. Where seen in the upper levels fragmental rock seems to form a relatively small proportion of the lode, and the areas between the fragmental portions are “tight” and poor. The mineralization was similar to that in the Mass mine. No records of the grade of rock or production are available.

SOUTH LAKE MINE

The Butler lode has been opened to a small extent in the South Lake mine from the surface to the 600-foot level. It is stated in the company reports that the openings made on the lode before operations were suspended were encouraging and that it gave the most promise of all the lodes in the mine. Rock milled in 1918 amounted to 7,694 tons and averaged 28 pounds of copper to the ton. It is not stated to what extent this rock was selected.

LAKE MINE

Development work on the Butler lode was done in the Lake mine from 1917 to 1919 through a crosscut on the 600-foot level of the Knowlton shaft. The lode was opened for about 1,400 feet along the strike and was reported to contain stretches of fair copper ground. The lode had been earlier opened by the No. 1 and No. 2 Butler shafts from the surface to the third level and for about 1,000 feet along the strike. Some stoping was done on the first and second levels, but no record of the results is available.

NORTH LAKE MINE

The North Lake Co.’s report for 1918 states that the Butler lode was cut in the 800-foot crosscut and followed by a drift for 30 feet. It was said to contain an encouraging amount of copper.

EVERGREEN LODE

MASS MINE

In the Mass mine the Evergreen lode (pl. 46) has been opened for about 3,500 feet along the strike. It has been rather extensively opened down to the eleventh level from shaft B and to a lesser depth and lateral extent from shaft A. There was no good opportunity to examine this lode in its best-mineralized portions. It is evidently fragmental, though not so highly fragmental as the Butler lode, and in places is coalescing. The fragmental part of the lode is of the rather coarse trappy type. Its mineralization was similar to that of the other lodes of the series. Quartz, calcite, pumpellyite, epidote, and feldspar are the common minerals. Like the adjoining lodes, this lode is cut in the Mass mine by numerous fissures. All are mineralized, and some contain considerable copper. The copper is coarser than in the Butler lode, yielding a larger proportion of mass—in fact, stamp rock is relatively unimportant. The copper is said by Mr. Walker to show a slight tendency to occur in shoots I with a southwesterly pitch.

The production from this lode, in recent years at least, has been much less than that from the Butler lode.

ADVENTURE MINE

In the Adventure mine the Evergreen lode has been opened for a few hundred feet on the adit level and to a slight extent on the sixth level. Little stoping has been done in this mine. The lode where seen in the adit level is fragmental but relatively thin. It contained copper rather persistently for a foot or so near the hanging wall.

SOUTH LAKE MINE

The Evergreen lode was cut in the South Lake workings, but no record of its character as there shown has been found.

LAKE MINE

In the Lake mine the Evergreen lode was cut on the 600-foot level from the Knowlton shaft and opened for about 700 feet along the strike. The report of the company for 1919 states that the lode as opened is very encouraging and is considered the best of the series as opened in the Lake mine. A stope over 200 feet long was started. Small test shipments, roughly picked at the surface, yielded from 18 to 34 pounds to the ton.

NORTH LAKE MINE

The Evergreen horizon was reached in the North Lake workings, but no description of the character of the lode is available.

KNOWLTON LODE

The Knowlton lode (pl. 43) has been most extensively opened in the Mass, Adventure, and Lake mines. It was seen in only a few places in the Mass mine, where it is of the fragmental type. As judged from the material on the dumps, it is fragmental in the other places where it has been opened.

MASS MINE

In the Mass mine the Knowlton lode has been most extensively opened from shaft C. On the third level a drift has been carried on the lode for about 2,000 feet. The lode has been largely stoped for 200 to 300 feet each side of shaft C to the eighth level. In shaft B the lode has been opened on the fourth, seventh, tenth, and eleventh levels, but little ground has been stoped. From shaft A it has been opened on the tenth level only. Near shaft C, according to Mr. Walker, it was of good grade.

ADVENTURE MINE

The main operations of the Adventure mine were on the Knowlton lode. In Nos. 1, 2, and 3 shafts the lode was opened for about 2,000 feet along the strike, and in No. 3 shaft it was opened to the thirteenth level. Only a relatively small proportion of the ground opened was stoped. The largest areas stoped were near No. 2 shaft to the tenth level and midway between Nos. 3 and 4 shafts on levels 7 to 10.

No. 4 shaft was supposed to be located on the Knowlton lode, but later a lode was found about 60 feet from the hanging wall of the one on which the shaft was sunk, and it was thought that this might be the Knowlton. The lode as opened in the Adventure mine has averaged rather low in copper. Prior to 1906, according to the company's report of 1907, all rock stamped averaged 12.29 pounds to the ton; in the first half of 1907 it fell to 8.7 pounds, but it improved during the second half of that year, when the mine was closed. The mine was operated for a short time in 1916-17 but was soon closed again.

LAKE MINE

The Knowlton lode has been opened at the Lake mine for about 1,200 feet along the strike and as deep as the sixth level in the main Knowlton shaft. Stoping has been done near this shaft from the first to the sixth levels. Some areas of fair ground were said to have been opened.

MICHIGAN MINE

A lode that is locally known as the Butler lode but appears to be higher, possibly at the Knowlton horizon, has been opened by shaft E of the Michigan mine to the eighth level and for a maximum distance along the strike of about 1,400 feet. The most extensive stoping has been done in what appears to be a westward-pitching shoot that crosses the shaft below the fifth level. (See pl. 43.) As indicated by material on the dump the lode is fragmental, and the character of mineralization is similar to that at other places where the lode has been opened.

OGIMA LODE

The Ogima lode (pl. 44) has been opened to a slight extent in shafts C and B of the Mass mine and in the Adventure mine. It contains patches of fragmental rock, and some of these are fairly well mineralized. The openings on the whole have apparently not been encouraging.

OTHER LODES

There has been slight development of the Merchant and North Butler lodes in the Mass and Adventure mines and of a lode in the foot of the Evergreen at the Lake mine. These lodes are somewhat fragmental and in places carry copper, but as yet they have offered little encouragement to extensive development.

FOREST ("VICTORIA") LODE

The statements regarding the Forest lode (pl. 47) are based on a brief visit to the Victoria mine in August, 1923, on the mine maps and records, and on statements by the late George Hooper, superintendent during the later operations, and by Charles Hooper.

PRODUCTION

The Victoria mine, on the Forest lode west of Ontonagon River, is the westernmost mine on the main range that has made a notable production. It was also one of the earliest producers in that part of the district.

Production of Forest lode in Victoria mine to end of 1923

Period	Rock treated (tons)	Copper produced (pounds)	
		Total	Per ton of rock
1855–1878	------------	375, 279	------------
1904–1923	1, 700, 518	19, 649, 134	11. 55
	------------	20, 024, 413	------------

GEOLOGIC HORIZON

The Forest lode is one of the series a short distance above No. 8 conglomerate, but with which one, if any, of those developed to the east it is to be correlated is not certain, and it is therefore considered separately. It is low in the series and probably near the Evergreen horizon. This lode has been slightly prospected for several miles to the south on the Tremont-Devon, Cass, and other properties but not extensively developed.

CHARACTER OF AMYGDALOID

Where seen in the Victoria mine the lode shows alternations of areas of rather thin cellular to coalescing amygdaloid with smaller areas of fragmental rock. The areas of fragmental rock seemed to bulge rather deeply into the underlying material, but Mr. Hooper stated that there were bulges of this character into the hanging wall also. The fragmental parts of the lode are 50 feet thick in places. The thicker masses of fragmental rock are irregularly distributed in the developed area, though they show some tendency to form shoots.

MINERALIZATION

Quartz, pumpellyite, epidote, and calcite are the most abundant minerals associated with the copper. Prehnite is fairly abundant. The rock alteration is mainly of the quartz-pumpellyite type.

Much of the copper occurs as relatively large masses. Mr. Hooper stated that in the later operation mass copper had run as much as 50 per cent of the total production and that the stamp rock was of low grade, carrying less than 10 pounds of copper to the ton. The thick bulges of fragmental rock are by far the richest portions of the mine, though Mr. Hooper stated that such rich areas have not yielded a very large proportion of the total output. The richness of the ground seems to show a close relation to the degree to which the lode is fragmental.

EXTENT OF DEVELOPMENT

The lode has been opened in the Victoria mine for about 3,800 feet along the strike and to the twenty-eighth level. The area in which extensive stoping has been done is considerably less, as can be seen by reference to Plate 47.

Some work was done in the early days on the Tremont-Devon property, west of the Victoria, and more recently diamond drilling has been done in order to locate the Forest amygdaloid. An amygdaloid that was thought to be the Forest was encountered and was reported to contain some copper.

LAKE LODE

PRODUCTION

The Lake lode (pl. 48) was located by diamond drilling in 1907. Development began in 1908, and the first production was made in 1909. From 1909 to 1918. when production was suspended, the Lake lode had yielded 7,326,227 pounds of copper. The yield ranged from about 16.0 to 26.5 pounds per ton of ore milled and averaged about 23 pounds. The rock was sorted to a varying degree. The company's report for 1918 states that "All new stopes opened in the Lake shaft showed a steadily decreasing copper content of rock. * * * In the newer stopes 5 or 6 tons had to be discarded for every ton shipped."

LOCATION

The Lake lode was discovered and first opened near the Keweenaw fault. Developments on the lode in the Lake and South Lake mines show that this portion of the lode is on the north end of a synclinal basin pitching southwest.

The openings on the lode were not accessible when the writers visited the region, and the statements concerning the lode are taken largely from the records and reports of the Lake and South Lake companies and from descriptions by Mr. C. J. McKie, manager of the Lake mine when operations on the lode were suspended.

STRUCTURE

The general structure of the area is that of a broad syncline lying between the northward-dipping series of the Evergreen Bluff, to the north, and the Keweenaw fault, to the south. The main workings of the Lake mine are around the north end of this basin, and those of the South Lake mine are on the north side of the basin, where the beds dip to the northwest and southeast from the axis of an anticline that strikes about with the general trend of the range.

CORRELATION

In the present stage of development there is possibly some uncertainty as to the exact correlation of the Lake lode with the lodes north of the anticline, which have the normal northerly dip of the range. It seems clear, however, that the Lake lode is one of the series of lodes above No. 8 conglomerate, and probably it is near the Evergreen lode of that series. A lode which may or may not be the Lake lode has been opened at the Algomah mine, west of the Lake mine, on the south side of the Lake mine basin, at the general horizon of the Lake lode.

CHARACTER

The Lake lode is distinctly of the fragmental type, and, like the Evergreen and most of the succeeding lodes, where they have been opened, it shows great variation in thickness from place to place. In some places it is apparently thick and fragmental; in others the amygdaloid has nearly disappeared.

The lode has been developed in the Lake mine for a distance of about 3,500 feet along the strike and down to the eleventh level. Some copper is said to be present throughout these openings, but the copper content was highest for a distance of 500 to 600 feet north and south of the main shaft, where 25 to 30 per cent of the rock has been stoped. It is reported that some copper was found in the drift on the Lake lode in the South Lake mine, but no stoping was done.

The fragmental amygdaloid of the Lake lode was brown and well oxidized. The principal minerals associated with the copper are quartz, pumpellyite, and calcite, which are accompanied by some epidote and a little red feldspar. The alteration of the lode rock was typically of the quartz-pumpellyite type.

ALGOMAH LODE

Operations on the Algomah lode began in 1910, but the only production has consisted of test shipments. A shipment of 74,560 pounds of ore made in 1914 yielded 18 per cent of copper, according to the company's report for that year.

The shaft on the Algomah lode is on the south side of the Lake mine basin, at the general horizon of the Lake lode and only 60 feet from the Keweenaw fault. Whether or not this lode is the same as the Lake lode has not yet been determined. Near the surface the lode dips 60° N. The shaft was not accessible at the time of the writers' visit to the district. In a short level about 30 feet below the collar of the shaft the lode is mainly cellular, with small areas of fragmental amygdaloid. The rock showed the pumpellyite rock alteration characteristic of many of the lodes in this part of the district. The company's reports, however, state that little native metal was found but that the copper was nearly all combined as black oxide, melaconite, green carbonate, malachite, and silicate. The ore seen on the dump corroborates this statement.

The lode has been developed for about 2,000 feet along the strike on the first level. About 1,000 feet north of the shaft the drift on the amygdaloid entered the Keweenaw fault, which was followed for some distance. The shaft was sunk to a depth of 558 feet, and a crosscut was driven north from the second level for about 950 feet to explore for other lodes.

BALTIC LODE

HISTORY AND PRODUCTION

Important development of the Baltic lode (pl. 49) began at the Baltic mine about 1898. The Trimountain mine and the Champion mine began production in 1902. Originally the three mines were operated under separate organizations, but at present the Copper Range Co. owns the Baltic and Trimountain and one-half of the Champion; the other half of the Champion is owned by the St. Mary's Mineral Land Co. The Copper Range Co. also owns the Atlantic mine. The following table shows the production from the mines and dividends from the beginning of operation to the end of 1925. A more detailed statement of production is given in the statistical section.

Production and dividends from the Baltic lode,[a] 1898–1925

Mine	Period	Rock treated (tons)	Refined copper (pounds) Total	Refined copper (pounds) Per ton	Dividends Total	Dividends Per pound of copper (cents)
Baltic	1898–1916	8, 672, 553	200, 584, 164	23. 13	$7, 950, 000	3. 96
Do	1917–1925	1, 820, 612	62, 939, 547	34. 57	} [b] 2, 084, 772	3. 23
Trimountain	1924–1925	43, 625	1, 343, 303	30. 79	}	
Do	1902–1923	6, 703, 079	139, 697, 289	20. 84	3, 250, 000	2. 33
Champion	1902–1925	14, 156, 309	438, 403, 286	30. 97	29, 070, 260. 96	6. 75
		31, 396, 177	842, 967, 589	26. 91	42, 355, 032. 96	5. 02

[a] Does not include production from Superior lode.

[b] Copper Range Co. Estimated.

The relatively high copper content of the rock treated from the Baltic lode as compared with that from the other amygdaloid lodes of the district is due mainly to the present method of mining, which permits discarding underground a relatively large percentage of poor rock. The table of production by years (pp. 79, 82) shows the change in copper content of rock treated resulting from the development of this method of mining. The method has been described and the results discussed by Denton and Schachf,[12] of the Copper Range Co., who show that for the period 1915-1921 as compared with 1908-1914 the yield per ton of rock treated increased from 24.8 to 37.2 pounds, or 50 per cent. The rock recovered per square foot of lode decreased from 1.54 to 1.40 tons.

The lode has been developed in the three mines for about 20,000 feet along the strike and in depth to the twenty-seventh level in the Champion mine, the thirty-sixth level in the Trimountain mine, and the thirty-ninth level in the Baltic mine.

EXTENT AND CORRELATION

The Baltic lode has been opened through the three mines of the Copper Range Co.—the Baltic, Champion, and Trimountain. North of these the Atlantic Mining Co.'s Section 16 explorations were presumably at this horizon, and farther north the Superior and Houghton Copper mines are at the general horizon of the Baltic lode and probably on that lode. Still farther north an amygdaloid at this horizon has been prospected by the Isle Roy ale Copper Co., and north of Portage Lake by the Arcadian Consolidated Copper Co. The identification and correlation of the Baltic lode becomes increasingly uncertain with increasing distance from the principal mines on the lode.

South of the Copper Range Co.'s mines an amygdaloid at the Baltic horizon has been prospected at the Globe and Challenge mines. The No. 3 conglomerate is not developed at these localities, and the correlation is somewhat doubtful, but the horizon has certainly been reached at the Globe, not so certainly at the Challenge.

BALTIC FLOW

The Baltic flow at the Copper Range Co.'s mines is an ophite 150 to 200 feet thick. It varies considerably in thickness from place to place.

Resting on the Baltic flow in the developed area are a number of thin disconnected flows. Some of these seem to thin out both up and down the dip and along the strike; others are as yet only partly outlined. Examples of those that seem to thin out are found in the upper levels of the

Trimountain mine, and examples of both kinds in the south end of the Champion mine.

[12]Denton, F. W., Development and extraction methods for Lake Superior copper deposits: Lake Superior Min. Inst. Bull., 1922, pp. 26-42. Schacht, W. H., Mining methods of the Copper Range Co.: Am. Inst. Min. and Met. Eng. Trans., vol. 72. pp. 346-370, 1925; Lake Superior Min. Inst. Bull., 1922, pp. 56-79.

These small flows apparently occupy and tend to fill depressions in the surface of the main flow. This is indicated by the fact that the distance from the No. 3 conglomerate, beneath the Baltic flow, to the top of the highest of these flows and to the top of the Baltic flow where they are absent, is far more uniform than the distance from the conglomerate to the top of the Baltic flow measured both where the overlying flows a present and where they are absent. The relations suggest that these small flows may be gushes from the main flow that were forced out after a considerable crust had formed on it but while most of the interior was still fluid. The gushes tended in part to fill hollows in the original surface of the flow, and in part they possibly caused the crust on which they flowed to settle into the fluid portion beneath, thus lowering the top of the main flow at these places.

Above the main Baltic flow and the "gush" flows resting on it is a flow that has a thickness of 40 to 60 feet where it has been cut in the developed area. The Baltic West lode is at the top of this flow.

STRUCTURE

FOLDS

The most pronounced structural feature in the Copper Range Co.'s mines is a broad anticline whose crest passes between the Baltic and Trimountain mines. This fold causes a very sharp change in strike, amounting to about 30°, between these two mines and in the south end of the Baltic workings. In this area the ground is much broken by faults and slips, and these probably displace the lode considerably, though present developments do not make this certain. In the south end of the Baltic mine the lode swings around in a zone of considerable fissuring and assumes the general strike that it has in the Trimountain mine, but if continued on this strike it would not meet the lode in the Trimountain mine. This suggests an offset between the Baltic and Trimountain mine. (See pl. 10.)

CROSS FAULTS AND SLIPS

In all the mines there are faults or slips with strong clay gouges striking nearly across the lode; most of these have steep dips, though a few dip as low as 30°. The smaller slips have caused but little displacement of the lode, and a drift carried on the general strike usually reenters the lode a short distance beyond such a slip, or the displacement may be so slight that the lode is not lost.

On some of the slips, however, there is a displacement of as much as 60 to 70 feet—for example, in the lower levels of the Baltic mine between No. 4 and No. 5 shafts and in the south end south of No. 2 shaft. The faults do not show a uniform direction of displacement. In many of the smaller faults the block north of the break is offset to the west, but a strong fault south of Baltic No. 2 shaft has moved the south block relatively westward.

Examples of the cross breaks with heavy clay gouges, together with vein minerals, are to be seen at the south limit of developments in the Champion mine and the north end of the Baltic mine. Some of the fissures in the Trimountain mine also have strong gouges, and, as already noted, there is apparently much fissuring with gouges in the area between the Baltic and Trimountain mines, where the lode makes a sharp change in strike, and the area of the Atlantic Co.'s Section 16 exploration north of Baltic is said to be much broken and fissured.

STRIKE FISSURES

Throughout the mines there are numerous fissures that strike with the lode or nearly so and dip more steeply than the lode, or from 75° to 90° where the lode dips 70°. These fissures are seen in the openings in the lode and in the crosscuts on both sides of the lode. In the long hanging-wall crosscut on the seventh level of the Champion mine such fissures are numerous near the lode but become less numerous with increasing distance from it. They are numerous and strong in the crosscut back of No. 4 shaft in the Baltic mine, but less numerous and weaker above the Baltic lode. This increase in abundance of strike fissures toward the Keweenaw fault, which is a few hundred feet southwest of the Baltic lode, suggests that the fissures may have been formed at the same time and by the same forces that produced the fault.

CHARACTER OF BALTIC AMYGDALOID

Although the writers were not able to examine the Baltic lode over large areas in the older worked-out portions of the mines, it is fairly clear from the examinations made and from descriptions by those familiar with the older workings that the lode is of the fragmental type.

Like all the other fragmental amygdaloids, the Baltic lode shows notable variations in the quantity of fragmental material from place to place. In many places the lode is 50 feet or even more in thickness and is composed of fragmental amygdaloid throughout; in other places it is but a few feet thick and is composed of rather coarse trappy fragments. Locally the spaces between the large fragments are filled with tongues from the hanging flow that extend for some distance below the top of the amygdaloid. In still other places the lode is cellular, with slight tendency to fragmental character. As in the other fragmental amygdaloids, unusually thick parts of the lode tend to bulge both to the hanging wall and the footwall.

This variation appears in both a small and a large pattern. In an area of prevailingly thick, notably fragmental amygdaloid, there are areas of thin and trappy or cellular amygdaloid, and in an area of prevailingly thin trappy amygdaloid there are areas of fairly typical fragmental amygdaloid. In the larger pattern the largest areas of thick fragmental amygdaloid occur in the Champion mine and in the upper levels of the Baltic mine. In the lower levels of the Baltic, in the Trimountain, and in the lower levels of the northern part of the Champion mine the lode contains on the average less fragmental material, though there are areas of markedly fragmental amygdaloid. In the smaller pattern there is a distinct tendency for the areas of abundant and less abundant fragmental material to form "belts" or "shoots" wdth a rather low southerly pitch. This tendency is particularly apparent in the Trimountain mine but is also evident in the Baltic and Champion mines. Whether or not this tendency is also present in the larger pattern is not clear in the present state of development. There is, however, a suggestion of it in the lower levels of the Baltic mine, where the lode contains a relatively small proportion of fragmental rock.

Where the small overlying flows or "gushes" are present, the lode beneath them seems to average thinner than where they are lacking. In places, at least, there seems to be especially thick fragmental amygdaloid around the margins of such flows, as if they had filled in depressions underlain by relatively thin amygdaloid surrounded by ridges of thick amygdaloid. The amygdaloid of these "gush" flows averages thinner and is more cellular than that of the main flow, which is probably to be expected from their origin.

The lode varies greatly in thickness. In the Champion mine in numerous places it is 50 feet thick and in some places even more; the average stoping width is about 26 feet.[13] In the Trimountain mine the average is about 16 feet. In the upper levels of the Baltic mine the lode averaged 20 to 23 feet, but in the bottom of the mine it is relatively thin and cellular.

OXIDATION

The Baltic lode is well oxidized though distinctly less so than the Kearsarge lode. The markedly fragmental rock, where not bleached by mineralizing solutions, is brown to reddish and well oxidized throughout. Trappy fragmental rock and cellular rock are usually less oxidized, though the tongues from the overlying flow that fill the spaces between coarse, trappy fragmental rock are commonly distinctly oxidized and give the lode a reddish appearance.

[13]Schacht, W. H., op. cit., p. 5

MINERALIZATION

MINERALS

The minerals of the Baltic lode are few. The abundant minerals associated with copper are quartz, pumpellyite, epidote, and carbonate—both calcite and an iron-bearing carbonate. Locally sericite is plentiful as in the south end of the Champion mine on the ninth and tenth levels. It is present but not abundant in many other places in all the mines. Laumontite is present in many fissures and locally in the lode. Other zeolites were not noted and certainly are relatively rare. Prehnite is present but is not abundant except in some fissures. Orthoclase, which is abundant in many other lodes and in the Superior mine, to the north, is almost entirely lacking in the Copper Range Co.'s mines. Datolite was not noted. Sulphides of copper are unusually abundant in all three mines. Their characteristic occurrence is in the fissures that dip 75° to 90° and strike nearly parallel with the lode, and they are likewise present in cross fissures. They also occur in the lode in the same manner as the copper, but this type of occurrence is rare. It was seen best in the Trimountain mine, on the twelfth level, in the stope south of No. 4 shaft from the end of the stope to No. 2 mill, where most of the copper in the lode is chalcocite associated with iron carbonate of the same type as occurs in the fissures. Chalcocite is by far the most abundant sulphide in the fissures, but bornite is not rare. Chalcopyrite is reported to occur in a few places.

The mineral most characteristically associated with the sulphides, both in lode and in fissures, is an iron-bearing carbonate. This mineral usually forms on the walls of the fissures, with the sulphides in the center. A similar relation exists where sulphide forms in the lode; the sulphide is surrounded by the iron carbonate. The iron carbonate is far more widespread than the sulphide. Over large areas it has permeated and replaced the amygdaloid, so that the rock, when exposed on the dumps, quickly turns brown from oxidation of the iron in the carbonate, as can be readily seen on the dumps of the Baltic mine. In many places copper is associated with the sulphides. Usually it occurs at the margins of the sulphide veins, but it may occur with quartz in the center of a vein. Where a vein branches and dies out in fragmental lode rock, chalcocite may give place to copper in the extreme ends. In the mass copper fissure in Trimountain No. 2 shaft, twenty-fifth level south, the mass copper was found near the intersection with the lode; where the fissure was followed into the footwall trap chalacocite appeared, though copper was still present. Only a relatively small amount of copper was present in both forms away from the lode.

Barite has been found in the Baltic lode but here as elsewhere is rare except in some of the fissures. The principal commercial occurrence of copper is in the lode, where it is irregularly distributed through the amygdaloid in bodies ranging from minute specks to masses several tons in weight. Most of the copper in this lode is in relatively small masses. Schacht[14] gives the percentage of the various sizes of copper produced as follows:

	Per cent
20 pounds or more	6
Less than 20 pounds but over ½ inch	9
½ to ¼ inch	22
¼ inch to 20 mesh	13
20 to 60 mesh	25
Below 60 mesh	25

[14]Op. cit., p. 5.

Large masses of copper have been found in two fissures at and near their intersection with the lode. Near Trimountain No. 2 shaft a mass fissure was mined from above the twenty-fifth level to the twenty-seventh. It is said that most of the copper was found just below the Baltic lode. Mass copper has also been mined from a fissure in the West lode of the Baltic mine, above the twentieth level. The fissure strikes nearly parallel with the lode but dips more steeply. The copper was in the hanging wall of the West lode. The fissure is of the same system as those that carry chalcocite, but it carried no sulphide so far as was noted. Mass copper in considerable quantity is said to have been recovered from strike fissures in the Champion No. 2 shaft. The copper is said to have occurred mainly in the trap below the lode.

ROCK ALTERATION

The characteristic rock alteration is of the quartz-pumpellyite type, with varying amounts of epidote. Wherever copper is present the lode is bleached, usually to the light-green color characteristic of abundant pumpellyite. This type of rock alteration is more fully discussed on page 107. Alteration of the same type occurs along the fissures both in the lode and in the adjacent trap rock.

RELATION OF MINERALIZATION TO CHARACTER OF LODE

In a broad way there is a close relation between character of amygdaloid and degree of mineralization. Rich ground is formed in thick fragmental amygdaloid. Thin trappy fragmental amygdaloid and cellular amygdaloid are commonly poor. The thick fragmental amygdaloid is not invariably rich, but thin or cellular lode is nowhere known to be rich over more than small areas.

The largest areas of thick fragmental amygdaloid opened are in the Champion mine and in the upper part of the Baltic mine. These are also the richest areas developed on the lode. In the Trimountain mine and in the lower part of the Baltic the lode is less fragmental and is not so well mineralized. In this respect the Baltic lode does not differ from other mineralized fragmental lodes.

RESULTS OF OPERATION

The variation of copper content with thickness of lode is shown by the data published by Denton[15] and Schacht[16] on the results of operations to 1921 on the richest and poorest units of operation on the Baltic lode.

Results of operation of mines on Baltic lode

	Champion	Trimountain
Average thickness of lode feet	26	16
Ore per square foot of lode tons	1.36	0.98
Copper per square foot of lode pounds	44	21
Productive lode area per cent	66	48

[15] Denton, F. W., op. cit., p. 42.

It is readily seen that the thicker parts of the lode have been the more productive. The Baltic mine is intermediate in character and productivity between the other two.

BALTIC WEST LODE

The Baltic West lode is the first amygdaloid above the Baltic lode. The underlying trap is from 40 to 60 feet thick, fine grained, and brownish. The amygdaloid of the portion opened, mainly in the Baltic mine, is of the fragmental type and is similar in character to the thinner parts of the fragmental amygdaloid on the main Baltic lode.

There have been no large areas developed on this lode comparing in thickness with the thick fragmental Baltic lode of the Champion and upper levels of the Baltic mine. There is some suggestion in this lode, as in the main lode, that the amygdaloid is in areas or belts of moderately fragmental and slightly fragmental or cellular lode. The present developments do not give much idea of the trend of such belts, but apparently if present they do not pitch very steeply.

The results of mineralization and rock alteration are entirely similar to those shown in the main lode, and there is the same general relation between mineralization and character of rock.

RELATION OF FISSURE MINERALIZATION AND LODE MINERALIZATION

Hubbard[17] long ago suggested that the strike fissures in the Baltic lode were the main channels through which the mineralizing solutions passed. He regarded the deposit as a true lode in the sense that it is a zone of closely spaced mineralized fissures rather than a mineralized amygdaloid.

[16] Schacht, W. H., op. cit., p. 5.

[17] Hubbard, L. L., Lake Superior Min. Inst. Proc., vol. 17, p. 229, 1912.

The close similarity of the minerals of the fissures and of the amygdaloid—the presence of abundant iron carbonate and quartz in both, and the same type of rock alteration in both—certainly gives good reason for supposing that the solutions that produced the fissure mineralization and the amygdaloid mineralization were very similar. The main difference—namely, the relative abundance of sulphides in the fissures and their relative scarcity in the amygdaloid—may be due to the oxidizing effect of the ferric iron of the amygdaloid, as has been discussed on page 129. This is particularly indicated where fissures finger out and are lost in fragmental amygdaloid. The mineral in some such fissures changes near the ends from chalcocite to native copper. It is also suggested by the presence in the amygdaloid over small areas of chalcocite instead of native copper, as has been noted especially in the Trimountain mine. These relations also suggest that the minerals in the veins and in the amygdaloids were formed during the same general period of mineralization, but there can be no doubt that some of the minerals in the fissures were deposited later than some of the minerals in the amygdaloid, and the minerals that now fill the fissures may have been deposited largely after the mineralization of the amygdaloid. Indeed, this must have been the case if the fissures were really the channels through which the mineralizing solutions entered the amygdaloid. The general subject of lode mineralization is discussed on page 124, where it is pointed out that in some of the lodes of the district there is no evidence to the present depth of development as to how the mineralizing solutions entered the lodes, but the mineralization seems to have been effected by solutions rising along the lodes.

It is entirely possible that solutions may have entered the Baltic and other amygdaloids with which mineralized fissures are associated, in part through the fissures that are now exposed and in part through fissures that entered the lode below the present depth of the mines.

SUPERIOR LODES

OCCURRENCE

The main Superior lode (pl. 48) is approximately at the same horizon as the Baltic lode and may be identical with it. It has been developed by the Superior Copper Co. and the Houghton Copper Co. Between the Superior mine and the Copper Range Co.'s mines, to the south, on the Baltic lode, are the Copper Range Co.'s Section 16 explorations, which are in a zone of considerable faulting, and no positive correlation of the beds has been carried across this zone.

Here as on the Baltic lode, both a main lode, called the Superior lode, and a west lode, called the Superior West lode, have been worked. The main lode has been opened in the two mines for a horizontal distance of about 6,000 feet and down to the thirty-first level in the Superior mine and about the fourteenth level in the Houghton Copper mine.

PRODUCTION

The following table gives the result of operations on the lodes to the end of 1925.

Production and dividends from the Superior lodes, 1906–1923

Mine	Period	Rock treated (tons)	Refined copper produced (pounds)		Dividends	
			Total	Per ton	Total	Per pound of copper (cents)
Houghton Copper Co.	1915–1917	49, 729	540, 052	10. 86		
Superior Copper Co.	1908–1920	1, 550, 474	30, 018, 271	19. 36	$649, 000	2. 16
		1, 600, 203	30, 558, 323	19. 09	649, 000	2. 12

CHARACTER

The main Superior lode, as indicated by the material on the dumps of the two mines and from descriptions, is a fragmental lode of distinctly scoriaceous character, with some shaly to sandy rock above the lode in the Superior mine.

The Superior West lode where mined is prevailingly fragmental but contains areas off cellular top. Outside of the main ore shoot the fragmental areas appear to be small as compared with the cellular.

MINERALIZATION

The most abundant minerals associated with copper in the Superior West lode are quartz, pumpellyite, epidote, calcite, and feldspar. Feldspar is unusually abundant in this lode, as contrasted with its scarcity on the Baltic lode. Laumontite is present in fissures and locally in the lode. Chalcocite and barite are present in small amount in fissures crossing the lode. The writers had no opportunity to examine the main Superior lode.

ORE SHOOTS

The ore shoot in the main Superior lode was developed in the Superior mine from the surface to the nineteenth level, but little of it was mined below the seventeenth level. The productive ground extended for 1,200 to 1,500 feet along the strike, but less than 50 per cent of the lode within the shoot was mined for ore. The general pitch of the shoot in the lode was to the north.

In the Superior West lode a shoot pitching south at a low angle was opened from the twelfth to the thirty-first level, but most of the ore mined was obtained between the twelfth and twenty-third levels. This shoot was developed along the strike for 1,000 to 1,500 feet, and in the most productive part between the twelfth and eighteenth levels a rather high percentage of the lode was mined. In the lower levels the shoot was small and "bunchy."

In 1920 the mine was closed, and the management stated that ore reserves had been exhausted and that prospecting for new ore had not been sufficiently encouraging to warrant further expenditure.

The Houghton Copper mine is north of the Superior mine, and the main openings are thought to be on the main Superior lode. The shaft is in the foot of the "East lode," which is probably the main lode. There has been some development in the upper levels on a lode lying farther east, and the Superior West lode has been opened in the Houghton ground to a slight extent by a drift from the nineteenth level of the Superior mine.

Only relatively small areas of the lode were stoped. The discard of rock broken in 1912 was 41 per cent, and the copper yield was low.

ISLE ROYALE

On the Isle Royale property an amygdaloid at the horizon of the Baltic lode has been opened by the A and Section 12 shafts, but without encouraging results.

FELSITE OF INDIANA MINE

DEVELOPMENT

The No. 1 Indiana shaft was begun in 1910 to explore an area of felsite which had been cut in diamond-drill hole No. 2 and from which a very rich core had been taken at a depth of about 1,400 feet. This exploration was carried on till 1916. The shaft was sunk below the fourteenth level, and openings were made at the 600-foot, 1,150-foot, and 1,400-foot levels.

The results of this work indicated that the felsite is an irregular body intruded into the traps. The felsite on the dump is a reddish fine-grained rock with scattered phenocrysts of quartz and feldspar. It is all much shattered, and there is also much felsite breccia, which probably came from the vicinity of the contact with the trap, where a considerable part of the exploration was carried on.

MINERALIZATION

Calcite is everywhere present along seams in the rock, and the felsite is bleached to a light gray. In some of the rock this bleaching has included the whole area between fissures. Oxidized copper minerals, carbonate (malachite), and silicate occur along many of the fissures. Where the oxidized minerals are present the original minerals have usually been entirely altered, but in some of the least altered portions chalcocite and "brittle" arsenical copper are present. It is probable that the oxidized minerals have been derived from both of these. In the larger fissures rather massive copper was found. There are masses several hundred pounds in weight on the dump.

No. 2 drill hole, from which the rich core was taken, was not identified underground, but the management believed when operations were suspended in 1916 that the core had come from a mineralized fissure or vein, like those encountered in the workings, and that the vein was probably not of great extent.

FISSURE DEPOSITS

HISTORY

Apart from the incidental extraction of copper from fissures in mines that exploit the amygdaloid and conglomerate lodes, there are some mining operations devoted primarily to fissure deposits. The first copper produced in the district was taken from the fissure deposits of Keweenaw and Ontonagon Counties. (See pls. 50-52.) Production began in 1845, and fissure mines were operating till about 1890. Except for the production from the Mass fissure by the Ahmeek Mining Co., beginning in 1909, there has been little operation on fissure deposits since that time.

PRODUCTION

The total recorded production of copper from fissures to the end of 1925 amounted to 199,853,000 pounds; of this total 61,315,000 pounds came from the Minesota fissure, of Ontonagon County, leaving a total of 138,538,000 pounds from the fissures of Keweenaw County. (For the production of individual fissures see p. 72 and the reports on mining companies in the statistical section, pp. 76-98.)

Of all the fissures that have been worked independently of the lodes in the district, only three have yielded a profit—the Cliff, Central, and Minesota. The Cliff paid $2,518,620 in dividends; the Central $2,130,000; and the Minesota $1,820,000, plus National $320,000, or $2,140,000. The Copper Falls paid $100,000 in dividends, but that was less than the assessments collected. The Phoenix paid $20,000. The Mass fissure in the Ahmeek mine has undoubtedly been profitable and probably would have been profitable if worked alone.

DISTRIBUTION

Plate 50 shows the relation of the Greenstone flow and the Allouez conglomerate to the principal fissures worked in Keweenaw County from Ahmeek to Delaware.

The fissures in the north end of the district are tension cracks on the folds. Thus there is a series of fissures near the crest of the Allouez anticline. From the Gratiot River gap nearly to the North American gap the Greenstone flow, which is perfectly exposed, is massive and almost without fissuring. Near the North American gap the great Keweenaw anticline begins, and fissuring of varying degrees of intensity is present from that locality to the end of Keweenaw Point.

DISTRIBUTION OF COPPER IN THE FISSURES

The only fissures that the writers have been able to study in any detail are those that cross the Kearsarge lode in the Ahmeek and Mohawk mines. Some of these contain native copper, others arsenides. On the Mass fissure only has drifting been carried far from the Kearsarge lode, though on a few others drifts have been extended as much as 200 or 300 feet from the lode.

There is strong evidence that the Kearsarge lode has been a large factor in causing the precipitation of the copper in the Mass fissure. This evidence consists first in the distribution of the copper in the fissure. The copper is most abundant at the intersection of the amygdaloid and the fissure and decreases with increased distance from the amygdaloid. On the footwall side it extends but a short distance, but on the hanging-wall side it extends much farther. Between the Kearsarge amygdaloid and the Kearsarge conglomerate there are no thick amygdaloid lodes, and no relation between copper and any amygdaloid but the Kearsarge has been noted. The second evidence of relationship is the alteration of the lode adjacent to the fissure. In general the lode near the fissure is chloritized and sericitized and contains less copper.

So far as can be determined from the meager amount of development, the same conditions hold true for the other fissures that cross the Kearsarge lode, both copper and arsenide fissures. The parts of the lode adjacent to the arsenide fissures contain some arsenides, and there can be little doubt that the copper arsenic solutions were traveling along these fissures and precipitated their burden at the crossing of the Kearsarge lode. The gradations from fissures high in arsenic to those low in arsenic, like the Fulton and other fissures, strongly suggests a common age and origin for all the fissure deposits.

The Mass fissure is crossed by a bedding fault about 200 feet stratigraphically above the Kearsarge amygdaloid. Most of the copper is found below this fault, but no sharp change in the amount of copper in the fissure after passing the fault has been recognized.

The most productive fissure deposits in the north end of the district have been found beneath the Greenstone flow, though some copper has been produced from fissures above the Greenstone flow. There has been no opportunity for direct study of these deposits, and the descriptions in the literature are far from complete. From such information as is available, however, there seem to be at least two possible causes for the special richness of the fissures beneath the Greenstone flow. The first is the presence of a fault or "slide," immediately beneath the Greenstone flow, at the horizon of the Allouez conglomerate, whether the conglomerate is present or not. This movement has produced a rather thick gouge, which may have acted as a dam to rising solutions and caused them to concentrate just beneath the Greenstone flow. Locally there is a displacement of the fissures along this fault, which causes the fissures to end against the gouge and would favor concentration of solutions.

The second possible cause is the same as already discussed for the fissures crossing the Kearsarge lode—namely, that the amygdaloid lodes intersected by the fissures were an influential factor in causing the precipitation of the copper.

From drill-core records at the Delaware, Cliff, and Central mines and descriptions of the Cliff mine, as well as from material on the mine dumps, it appears that there are favorable amygdaloids in the belt under the Greenstone flow. In some reports mention is made of the favorable influence of amygdaloids on the vein, which seems to have been pretty clearly recognized by the early operators. Furthermore, some of the veins above the Greenstone flow are correlated, though not certainly, with those below, as the Petherick and the Northwestern, the Cliff and the North Cliff; and doubtless others have continuations above the Greenstone flow. Above the Allouez conglomerate horizon the veins seem to be poor or barren until they reach the amygdaloids at the horizon of the Ashbed lode, which are the next higher thick amygdaloids. The fissure deposits associated with the Ashbed are not as large as those below the Greenstone flow, but it seems likely that the solutions passed through the Greenstone flow and overlying beds but did not deposit much copper till they reached the favorable environment of the amygdaloids at the horizon of the Ashbed lode. If this is true, it would seem that neither the Greenstone flow nor the "'slide" beneath it was everywhere a very effective barrier to the passage of ore solutions along these fissures. It may be noted, however, that apparently in neither the Cliff nor the Central mine has a largely productive deposit been found on the extension above the Greenstone flow. The extension of the Central fissure above the Greenstone flow has not been identified, but the supposed extension of the Cliff has been prospected without finding valuable deposits, though the fissure contains some copper where it crosses the Ashbed. The Cliff fissure is offset by a fault at the horizon of the Allouez conglomerate, and the same may be true of the Central. Such offsets would doubtless tend to limit the mineralization to the sections below the faults. From the detailed descriptions of the different fissure deposits beneath the Greenstone flow it appears that the fissures are not everywhere and probably not generally mineralized up to this flow or to the "slide " but have the maximum mineralization a short distance below the slide. The diamond-drill sections at the North American, Cliff, and Central mines show that the amygdaloids immediately beneath the Greenstone flow are not very thick or favorable as compared with those below the Houghton conglomerate. The fissures, however, probably averaged richer above the Houghton conglomerate than below it, so that while there is a general relation between thick amygdaloids and copper in the fissures, this relation is not close.

At several localities a slide has been reported at the horizon of No. 17 conglomerate and may have been a factor in the formation of fissure deposits in the Ashbed amygdaloid flows.

It appears that there is a very notable difference in the effect of the fissures on the amygdaloids near the crossing in the Kearsarge and on the amygdaloids to the north, under the Greenstone flow. The Kearsarge lode is relatively poor in copper near the fissure intersections, whereas both the Ashbed and the amygdaloids below the Greenstone flow are said to be best near the intersections of fissures. This difference is not necessarily inconsistent with the operation of the same causes. Apparently both the Kearsarge lode and the amygdaloids to the north were mildly mineralized near the crossings by the solutions that traveled along the fissures. To judge from what can be observed in the mines on the Kearsarge lode, these early solutions also altered the lodes where they mineralized them, destroying much of their favorable chemical character, so that when the later mineralizing solutions came up along the Kearsarge lode they encountered unfavorable ground near the fissures and hence did not deposit much additional copper in those parts of the lode.

In the Ontonagon district the fissures are nearly parallel with the strike of the beds. In the main Minesota or North branch, mineralization occurs in the fissure at and above the supposed intersection with the Minesota conglomerate, suggesting that in this deposit the character of the bed crossed by the fissure is the controlling factor. The position of the downward extension of the fissure is not certain. If the dip and strike of its known portion are maintained it cuts across the beds; but there is a possibility that it curves into the conglomerate bed and becomes a bed fissure.

From the foregoing statements it is apparent that a clear understanding of the cause of the localization of the copper in the fissures is of great importance in prospecting for this type of deposit. In the deposits at the Kearsarge lode crossings, for which the most definite information is available, the character of the lode seems to be the controlling factor. The deposits of which less is known, such as those under the Greenstone flow, afford reason to believe that the character of the lode is an influential factor, though the presence of the "slides" and the offsetting of the fissures, forming barriers, have aided in concentrating the flow of the solutions.

STATE OF DIVISION OF COPPER

The Mass fissure of the Ahmeek mine (pl. 51) differs from most of the other known fissures in the district in that it contains practically no stamp rock, whereas from the others the recovery from stamp rock was large. The approximate percentages which the several kinds of copper made of the total production from the different fissures are as follows:

Cliff, 70 per cent mass, 15 per cent barrel, 15 per cent stamp
Phoenix, 50 per cent mass and barrel, 50 per cent stamp.
Central, 50 per cent mass, 50 per cent barrel and stamp.
Northwestern (1854), about 30 per cent stamp.
Minesota (1866), 30 per cent mass, 43 per cent stamp.
Copper Falls, a large amount of stamp copper.
Robbins, mainly stamp rock.

At nearly all the mines stamp mills were regarded as essential parts of the plants. Rock was stamped from the Stoutenberg, Clark, Eagle River, Madison, Amygdaloid Mining Co., St. Clair, and other fissures, in addition to those mentioned above. In the early days rock was calcined in stone kilns before being stamped.

EXPLORATION OF FISSURES

INCENTIVE TO EXPLORATION

The total production of copper from fissures has been small as compared with that from lodes. Each of the principal lodes of the district has produced nearly as much as all the fissures together, and most of them much more. The total amount of the dividends from fissure deposits has also been modest as compared with those resulting from lode mining. The dividend per pound of copper, however—about 3.5 cents—is about the same as that of the lode mines. It is worth while, therefore, to consider whether any considerable veins remain unopened or but partly developed.

Examination of the records and of the field indicates that by no means all the wide fissures that are exposed in the Greenstone bluff have been extensively explored; that almost nothing is known of the extensive areas comprised in the "gaps" in the Greenstone flow; that the experience gained in the Central exploration indicates that valuable deposits may be found in fissures that make little show where they cross the Greenstone bluff; and that a second favorable belt for fissure exploration may possibly be present east of the one under the Greenstone flow.

A distinct advantage in fissure exploration is that the promising zone beneath the Greenstone flow is very definitely outlined, and other areas of possible promise might be outlined with equal definiteness. The cost of exploration would be much less than in the early days, when much money was expended in promotion, in many separate organizations, and in roads, mills, and other features that could now be partly eliminated. Altogether there seems good reason to expect that a comprehensive campaign of fissure exploration would result in the development of mines that would give a moderate return for the effort. It is hardly to be expected that any great mines would be developed on fissures.

GENERAL FEATURES OF EXPLORATION

In any general plan of exploration of the fissures of Keweenaw County, there are certain features that should be considered. Among the more important are (1) significance of the gaps in the Greenstone flow; (2) significance to be attached to the character of the fissures as they are exposed in the Greenstone flow; (3) influence of thick, fragmental, well-oxidized amygdaloids on the precipitation of copper in the fissures; (4) influence of faults or barriers on the localization of copper.

1. There is little doubt that the gaps in the Greenstone flow have resulted from weakness of the rock due to faults or fissures. Definite indication of this is seen in the displacement of the rocks and in the shearing of the rock bordering some of these gaps, as the Eagle River gap and the Central gap. Two of the gaps have been prospected, the Madison and the Amygdaloid. In the Madison a fissure was exposed, but little was done on it, owing to the difficulty of drainage. In the Amygdaloid the Drexel fissure was developed by the Amygdaloid Mining Co. and yielded considerable copper. Diamond drilling across the North American, Arnold, and Central gaps has shown fissures present in each. Therefore, so far as developments have been carried in the north end of the district, there is reason to suppose that the gaps may mark the location of fissures. On the Allouez anticline the strongest shatter zones, where they cross the Kearsarge lode, do not contain productive fissures. There are fissures in these zones, and what they contain in the belt under the Greenstone flow has not been determined.

The drilling of three of the gaps, the North American, Arnold, and Central, indicates that the gaps are due to fissuring and faulting, although in none is a wide shatter zone present. In the "road gap" at the Central mine there is a mineralized fissure; in the main gap, a fault with only a narrow fracture zone about 8 feet wide.

2. The Greenstone bluff and some of the ridges north of it are practically the only places where the fissures are naturally exposed, and it is important to know whether the character of the fissures as shown in the bluff is any indication of what is to be expected of them in the favorable zone below the Greenstone flow.

Naturally the fissures that appear largest in the Greenstone flow are the ones that have been chosen for prospecting. This prospecting has led to the development of one paying fissure mine, the Cliff; a second that would doubtless have paid under modern efficient management, the Phoenix; and several others that might have nearly or quite paid the cost of their development, as the St. Clair, the fissure mines at Delaware, and the Drexel. On the other hand, many of the other fissures prospected because of their prominence in the Greenstone flow have yielded little or no copper.

The most productive fissure, the Central, was not recognized where it crossed the Greenstone flow but was discovered in an outcrop about 600 feet south of this flow and in ancient pits which presumably were sunk on the outcrop of the vein. It therefore appears that too much reliance should not be placed on the appearance of a fissure in the Greenstone flow, but a more certain method and perhaps as cheap would be to drift on a favorable amygdaloid along chosen stretches of fissured ground with the idea of examining all the fissures of the area where they crossed the favorable zone.

3. There is reason to believe that the thick fragmental, well-oxidized amygdaloids had a favorable effect on the precipitation of copper in the fissures. Such amygdaloids are present in the belt under the Greenstone flow and may or may not have been the controlling factor in making this a favorable belt. That it is a favorable belt has been well demonstrated. The practical question is therefore not so much whether the amygdaloids under the Greenstone flow have exerted a favorable influence as whether similar amygdaloids elsewhere that have not been explored have exerted such an influence. There are thick amygdaloids below this belt at about the horizon of the Osceola lode, in which fissures have been prospected but little. The Central fissure was mineralized at this general horizon, but other fissures have not been examined where they cross this belt. (See accompanying sections.)

4. A fault at the base of the Greenstone flow offsets some of the veins. Any interruption of the veins along such an inclined plane would tend to produce a barrier and concentration of solution beneath it. Such a barrier condition would favor the formation of deposits, although the evidence from the fissures that cross favorable parts of the Kearsarge, the Ashbed, and the conglomerates in the south end of the district suggests that barriers may not be essential.

METHOD OF EXPLORATION

Selected areas along a thick amygdaloid could be prospected either by sinking a shaft and drifting, or in places by driving an adit that would permit exploration near the surface. The latter method would eliminate both pumping and hoisting and would serve in the examination of long stretches of territory, but probably sufficient depth to explore under the deeper gaps could not be obtained in this way, and it would give only very shallow exploration of the promising fissures, which would then have to be examined further by shaft.

SUGGESTED EXPLORATIONS

In the following paragraphs are suggested explorations which might determine the points outlined above and the results of which would of course influence any further consideration of the general problem.

At present all that is known about the influence of thick amygdaloids aside from that below the Greenstone flow is that the Osceola horizon where the Central fissure crossed it at depth was well mineralized and that the Vaughnsville fissure showed best in what was thought to be the Osceola amygdaloid.

It is of course possible to project any of the known mineralized fissures to the crossing of belts lower in the series and prospect at that point, but it would seem advantageous to use the information gained in prospecting the known favorable horizon in deciding how to prospect one that is little known.

FISSURE MINES AND PROSPECTS OF KEWEENAW AND ONTONAGON COUNTIES

Star.—Two miles south of Copper Harbor, in the E. ½ sec. 9, T. 58 N., R. 28 W., south of the Greenstone flow. Two shafts were sunk on the principal vein, 300 and 90 feet deep. These were connected by drifts and by an adit level for drainage. Little stoping has been done (1864). An amygdaloid belt 13 feet wide, carrying copper, was opened 150 feet east of the transverse vein. Another vein being prospected in 1864 carried rich barrel rock near the surface. D. S. Childs, the agent, reports opening two veins, one 700 feet to the west of the Star vein and one 600 feet to the east. The one to the west was opened 100 feet from the Greenstone flow, where it was 5 feet wide and well charged with copper. It was opened also 1,000 feet from the Greenstone flow, where it carried less copper. The recorded production of the Star Mining Co. is 17,938 pounds.

Clark.—South of Copper Harbor and north and west of the Star property. The veins bear N. 10° W. and have been mined on both sides of the Greenstone flow. Two veins were opened by adit and three shafts. Small masses of copper were frequently found, enough to give encouragement but not enough to pay costs. The recorded production is 187,915 pounds.

Iron City.—Southeast of Mosquito Lake, in sec. 14, T. 58, N., R. 29 W. Two shafts were sunk 30 feet apart, No. 1 to a depth of 300 feet, and connected by levels. The vein was wide but failed to yield copper.

Medora.—One mile southwest of Mosquito Lake, in the E. ½ sec. 17, T. 58 N., R. 29 W., immediately south of the Greenstone flow. The company was organized in 1851. Considerable work was done, but a relatively small amount of copper was found. Amygdaloid "floors" were said to be present as in the other mines.

Native Copper.—North of Delaware, in sec. 10, T. 58 N., R. 30 W. Worked on a vein crossing the Ashbed horizon but found nothing encouraging.

Conglomerate.—Under the names Northwest Copper Co., Pennsylvania Mining Co., Delaware Mining Co., and Conglomerate Mining Co. the veins and the Allouez conglomerate at Delaware were worked at different times. The Northwest Copper Co. began operations in 1847 and developed three fissures. To the end of 1859 it had expended $611,000, and its copper sales had amounted to $328,000. In 1861 the Pennsylvania Mining Co. was organized to take over the property. This company opened three additional veins and undertook extensive surface improvements, expending $126,000, but produced no copper. In 1863 part of the territory was sold to the Delaware Mining Co., under the same management. The two companies are said to have spent nearly $2,000,000 in the next few years but produced little copper. In 1866 the property was taken over by the bondholders. The two properties were in 1876 united as the Delaware Copper Mining Co. This company operated with little production till 1881, when it was reorganized as the Conglomerate Mining Co. The new company is said to have expended $1,500,000 in making surface improvements and opening the Conglomerate mine. The mine at present belongs to the Calumet & Hecla Consolidated Copper Co. Altogether more than $4,000,000 was spent, and to 1886 a total of 7,188,000 pounds of copper was produced. At no period in its history was the mine operated at a profit. Three fissures were developed to a considerable extent—the Stoutenberg, Delaware, and Hogan. The Stoutenberg was opened to the eighth level, the Delaware to the ninth level, and the Hogan to the fourth level. The geologic relations in all the fissures seem to have been essentially the same. The productive part of each was close under the Allouez conglomerate, though the fissures do not appear to have been mined into the Allouez conglomerate. The reports state that several amygdaloid "floors" were present in the mine and that the amygdaloids had a marked influence on the vein. The "floors" were also mined and apparently furnished a considerable part of the production. The maps show that the stoping on the amygdaloids decreased away from the fissures, indicating that the richness of the ground decreased in the same direction.

Connecticut.—West of the Delaware. Owned by Amygdaloid Mining Co. Opened by three shafts— No. 1, near Greenstone flow, 60 fathoms; No. 2, 20 fathoms; No. 3, 6 to 7 fathoms—and an adit. Adit level driven 551 feet; 10 fathoms below adit, drifted 181 feet; 20 fathoms below adit, 514 feet; 30 fathoms below adit, 147 feet. Total recorded yield 116,800 pounds of copper.

Amygdaloid.—Just west of the Delaware. Opened in 1860 and operated through 1878. No statement or map showing the amount of development has been found. Recorded production 1,541,180 pounds.

Eagle Harbor.—Explored a vein crossing the Greenstone flow, midway between the Madison and Amygdaloid gaps. It was reported to carry good copper above the Ashbed horizon in sec. 8. It crossed the Greenstone flow in low, poorly exposed ground, and the explorations (1866) failed to locate the fissure. A vein through Madison gap was opened in the low ground. It carried some copper but was not further explored (1865) on account of the difficulty of working. A vein west of the gap was opened by a shaft and adit to a depth of 72 feet. The vein was found 3½ feet wide but was said to be in "hard rock" and unprofitable. The Essex fissure, which passes through a gap, was explored in sec. 16 by an adit. At 500 feet from the Greenstone flow a shaft 100 feet deep was sunk and a drift started north (1865?). The vein, where followed by the adit, was reported to be rich in stamp copper, but apparently further development did not reveal a valuable deposit. Another vein farther east, reported as 3 feet wide and yielding good stamp copper, was opened in 1866. No production is recorded from these explorations.

Madison.—The Madison Mining Co. operated on three fissures—the Perkins, 2,000 feet west of Madison gap, and the East and West veins, 4,000 feet west of Madison gap. The East or main lode has three shafts and an adit level. No. 3 shaft is opened to the 20-fathom level, No. 2 to the 30-fathom, and No. 1 only to the adit level. Shafts were connected on the adit, 10-fathom and 20-fathom levels, and some stoping was done. The West lode was opened by shafts and winzes to the 20-fathom level with some stoping. It is reported that about $250,000 was expended. The recorded production was 72,000 pounds. The Madison gap was not explored except for a pit that located a fissure.

Dana.—The Dana fissure, about 4,000 feet east of the Central mine, was opened by an adit 780 feet long and by three shafts, but it proved unproductive.

Copper Falls.—The Copper Falls Mining Co. was one of the earliest in the district. It conducted operations on several fissures and on the Ashbed lode. At different times tracts have been set aside from the original grant and recombinations made. At present the ground belongs to the Arnold Mining Co. Altogether the Copper Falls Co. collected $1,000,000 from assessments and paid $100,000 in dividends. It has the distinction of being the only mine in the north end of the district above the Greenstone flow that has paid dividends, but it evidently was not a profitable undertaking. The most prosperous period was in the late sixties, when a small but rich area in the Owl Creek vein was being mined. This vein was developed by an adit that starts near the base of the Great conglomerate and extends through the trap series, probably into the Greenstone flow. There is some uncertainty from the old records as to the relation of the ore to the different types of rock. In general it may be said that the fissure was productive only in the vicinity of the Ashbed lode. Apparently nothing encouraging was found from the Greenstone flow to a short distance below the Ashbed and from a short distance above the Ashbed to the Great conglomerate. According to Marvine's Eagle River section, there were no thick amygdaloids between the Greenstone flow and the Ashbed amygdaloid. Above the Ashbed are some amygdaloids but apparently none as thick as that flow. It seems logical to conclude that the Ashbed amygdaloid was a factor in the enrichment of the vein at this point. The Ashbed amygdaloid itself is mineralized and was mined for 1,000 feet or more on both sides of the fissure. No statement has been found to indicate whether it was notably richer or poorer near the fissure, though the old stope map suggests better ground near the fissure than at a distance. Datolite is abundant in the Owl Creek fissure and in the Ashbed amygdaloid. As the Ashbed was mined for part of the time the production from the fissures is not known accurately, but it is estimated as follows: Owl Creek fissure, 7,283,000 pounds; Copper Falls fissure, 731,000 pounds; Old Copper Falls fissure, 86,000 pounds; Hill fissure, 501,000 pounds; Childs fissure, 32,000 pounds. It is estimated that the Ashbed amygdaloid yielded 17,706,000 pounds of copper.

Petherick.—The Petherick fissure is about 2,000 feet west of the Owl Creek fissure and has been developed in the same general stratigraphic horizon. It has been opened, so far as known, continuously by adit and shaft for about 2,300 feet along the strike and to a maximum depth from the outcrop at No. 6 shaft to the adit level of about 225 feet. (See pl. 50.)

No accurate record is available of the stoping on this fissure. There was some stoping on the Ashbed amygdaloid adjacent to the fissure workings, of which, too, there is no record. It is therefore not known how much of the production of the Petherick Mining Co. came from the fissure and how much from the Ashbed. As indicated by the material on the dump, datolite was abundant in the fissure and in the Ashbed adjacent to the fissure. In this respect the Petherick resembles the neighboring Owl Creek fissure.

Old Copper Falls.—The Copper Falls Co. began work in 1845 on the Old Copper Falls fissure. The outcrop was exposed in the falls of the stream. The work was continued till 1850, and a depth of 267 feet was attained. Some good ground was developed, but the production was small and the operations were unprofitable.

Northwestern.—The Northwestern Mining Co. began operations in 1845 on a fissure below the Greenstone flow and worked rather continuously till 1857; some work was also done later by this company on the original fissure and on the southward extension of the Central fissure. Assessments to the amount of $228,000 were collected, and copper to the value of about $75,000 was produced. The workings comprised four shafts, 109, 201, 215, and 225 feet deep, an adit 1,226 feet long, and levels Nos. 10, 20, and 30, respectively 944, 1,057, and 124 feet long. The recorded production is 313,000 pounds.

Central.—The description of the Central vein is compiled from the mine maps and from Hubbard's account. The Central mine was opened in 1854 and closed in 1898. During this period it yielded 51,875,527 pounds of copper, and the company paid about $2,130,000 in dividends. The mine is opened on a fissure vein striking nearly at right angles to the beds and dipping very steeply to the east in the upper levels and slightly less steeply in the lower levels. There is no pronounced gap or outcrop of vein in the face of the Greenstone bluff to indicate where the fissure crosses. It may be offset by a strike fault at or near the base of the Greenstone flow. The fissure was discovered by outcrops and in ancient pits about 600 feet south of the Greenstone bluff. The productive part near the surface was close under the Greenstone flow, though the minable portion nowhere seems to have extended to or into the Allouez conglomerate. With increased depth the mineralized portion gets farther and farther from the Greenstone flow. The ore shoot has its greatest extent along the strike of the fissure at about the 100-fathom level. Below that it narrows to about the 200-fathom level, where it again expands; it continues to the Kearsarge conglomerate at about the twenty-ninth level, where the fissure is displaced by a fault. The principal structural features are the main fissure and the strike fault at the Kearsarge conglomerate. The fault cuts out the Kearsarge conglomerate and offsets the vein below the fault 284 feet to the west. The fact that the thick conglomerate is completely cut out by the strike fault suggests a large movement of which the horizontal offset of the fissure is a small component. Below the fault what is regarded as the continuation of the fissure was found to contain but little copper, though the fissure appears to be wide. No direct statement is made in Hubbard's description regarding the age of the fault relative to the period of mineralization. As the breccia along the fault is mineralized, however, it is probable that mineralization followed the faulting.

No detailed description of the character of the amygdaloids intersected by the fissure has been found. Pumpelly briefly described those in the upper part of the mine. He mentioned three soft brown amygdaloids between the Calumet & Hecla conglomerate and the Houghton conglomerate. These are at about the horizon where the lode begins to widen out upward. The character of the amygdaloids below the Calumet & Hecla conglomerate is not known. Central diamond-drill hole No. 9, west of the mine, and the one at Arnold Gap (No. 11) show thick fragmental amygdaloids above and below the Houghton conglomerate.

The cause for the concentration at this point is susceptible of several explanations. If the faulting preceded the mineralization, it is hardly reasonable to suppose that the mineralizing solutions rose along the fissure below the fault and then jumped across to the portion above the fault. If mineralization preceded faulting and the movement was of great magnitude, a barren part of the fissure might be brought into contact with a mineralized part. The mineralized portion of the fissure is immediately above the point where the conglomerate is cut out. This, together with the fact that the crushed portion of the Kearsarge conglomerate is mineralized, has led to the suggestion that the solutions rose along the conglomerate and escaped into the fissure where the conglomerate was cut out. The reason for the variation in mineralization along the fissure is not clear, and little information is available concerning the character either of the fissure or of the inclosing beds to give a basis for an interpretation. The map shows, however, a distinct tendency for the expansions in the shoot to extend along the bedding rather than across it. This suggests an influence of the beds in precipitating copper. The soft brown beds noted by Pumpelly at about the horizon where the upper expansion occurs may have influenced the precipitation. Whether similar beds are connected with the lower expansion is not known. The mineralization did not extend to the Greenstone flow, and so far as can be judged from the map there is little evidence of the deflecting or damming influence of this flow.

There appears to have been some mineralization of several of the amygdaloids near the fissure, and the Calumet & Hecla conglomerate was well mineralized adjacent to the fissure at about the eighteenth level. Nowhere was commercial rock found to extend far from the fissure. In the Calumet & Hecla conglomerate ore extended about 40 feet on each side of the fissure. The Houghton conglomerate was reported as well mineralized, but no stoping was done on it.

Winthrop.—The Winthrop Mining Co. worked several years on a fissure in the SW. ¼ sec. 23, T. 58 N., R. 31 W., west of the Central mine. No production is reported.

Eagle River.—The Babbitt vein, 1,000 feet east of the St. Clair, was opened in 1880 by the Eagle River Mining Co., which put down two shafts, 275 feet apart, one close to the Greenstone flow. The recorded production is 49,678 pounds.

St. Clair (acquired by the Phoenix Consolidated Copper Co.).—The St. Clair vein is east of the Eagle River gap, and the mine is immediately under the Greenstone flow. A fault or "slide" branches from the Greenstone flow contact about 150 feet below the outcrop. It dips more steeply than the contact and thus diverges from it with increasing depth. At the 10th level the stratigraphic distance between the Greenstone flow and the fault is about 350 feet. Practically all the stoping has been done between the Greenstone flow and the fault. The stopes seem to extend up to the flow and in places cross the fault but have extended only a short distance below it. The mine was opened to the twelfth level. The vein is said to have been rich, carrying 2 to 3 per cent of copper, but it was narrow, and the mineralized area was relatively small. Under the conditions of operation it evidently did not pay.

Bay State.—The Bay State Co. operated on the Phoenix or Bay State fissure, south of the Phoenix mine, and was later absorbed by the Phoenix Co.

Phoenix.—The Phoenix Copper Co., now absorbed by the Keweenaw Copper Co., was organized in 1844 and was one of the earliest companies in the district. It operated on numerous veins and on the Ashbed amygdaloid. The total assessments by the old Phoenix and the Phoenix Consolidated are given by Stevens as $2,385,500, and the dividends as $20,000. The only really profitable operations seem to have been conducted for a few years in the early seventies on the Phoenix fissure.

Phoenix fissure.—The only description found of the rocks under the Greenstone flow in the Phoenix mine is that by Marvine. This description does not give the impression of any particularly thick amygdaloids in the mine. There is a belt of thin flows, but the amygdaloids are apparently small. The Allouez conglomerate is represented by a "slide." Extensive stoping has nowhere been carried more than 1,400 feet from the Greenstone flow along the level, or about 700 feet across the beds. Nothing has been seen in the reports to indicate where the richest ground was found. The vein evidently varied in grade from place to place, but there is no statement of the conditions accompanying this variation. Neither is it stated whether or not there was a notable change in grade from the surface downward. The deepest workings on the inclined shaft are at a vertical depth of about 1,000 feet. Stevens states that the yield from 1872 to 1885 was 473 pounds per fathom, or about 1.5 per cent. No mention is made of operations on amygdaloids.

Robbins or West.—The Bobbins or West vein was developed by the Phoenix Co. a short distance west of the Phoenix or Bay State vein. It has a more easterly strike than the Phoenix and cuts the beds at an acute angle. The mineralized belt, as indicated by the stope map, is 100 to 250 feet wide and 50 to 75 feet below the Allouez slide. The maps indicate but one amygdaloid belt, 300 to 350 feet below the stopes, but other amygdaloids are undoubtedly present. The mine has been opened to a vertical depth of about 600 feet. Some good ground was found, but as a whole it did not pay. The vein is said to have contained no mass copper, producing stamp rock only.

Old Phoenix.—A vein was encountered under the bed of Eagle River near the Ashbed crossing and followed for several hundred feet. One account of this vein describes the copper and silver as occurring with waterworn pebbles, suggesting a placer deposit. Others indicate that it is a vein that has been followed by the river. A few thousand pounds of copper and some silver was taken from this vein. It apparently was never developed at depth except where the Ashbed drift crossed its downward extension. There it is a thick calcite vein with some copper but not in commercial quantities.

Vaughnsville.—The Cliff Copper Co. opened the Vaughnsville fissure, nearly a mile south of the Greenstone flow. The strongest mineralization was found at the intersection of an amygdaloid supposed to be the Osceola.

Cliff.—The Cliff mine, on the Cliff fissure, was the first large copper producer of the Lake Superior region. Production began in 1845, when it yielded about 20,000 pounds of copper. The mine was operated, with the exception of an interval from 1870 to 1872, until 1883. It was idle from 1883 until 1906, when it was reopened and some amygdaloids in the upper levels were explored adjacent to the fissure. A total of 38,207,000 pounds of copper was produced, and the company paid $2,518,620 in dividends.

The productive portion of the Cliff fissure lies under the Greenstone flow. At the mine the Allouez conglomerate is represented by the "slide," a few inches of clay gouge. Immediately under the slide is a series of small flows numbered in the Cliff mine upward from 1 to 13. These have an average thickness of about 50 feet, and so far as can be judged from the old maps, from one-third to one-half of the rock in this belt is amygdaloid. The five beds next to the Calumet & Hecla conglomerate average about 90 feet in Thickness. The series of thin beds beneath the Greenstone flow form a relatively weak zone, as is indicated by the pronounced depression in the bedrock surface just south of the Greenstone bluff. The thickest amygdaloid, as indicated on the maps, is No. 13, the one immediately beneath the "slide." No. 9 is also indicated on the maps as a thick amygdaloid. No detailed description of the amygdaloids has been found, and it is therefore not known whether they are fragmental or how well they are oxidized. Examination of the dump indicates that there is at least one fragmental, well-oxidized amygdaloid. The diamond-drill section west of the fissure shows some thick fragmental amygdaloids below the Houghton conglomerate. The developments have been confined to beds above the Calumet & Hecla conglomerate.

The Cliff fissure cuts nearly at right angles to the beds and dips steeply to the east, with local reversal of dip. It is well exposed as a wide veined and shattered zone in the face of the Greenstone bluff and has been followed from a point south of the Cliff mine workings to the lake shore. In places in the mine workings it branches. There are two "slides" noted in the mine workings—one at the horizon of the Allouez conglomerate and one that reaches the surface at about No. 2 shaft, South Cliff. Both are essentially parallel to the beds, and both have displaced the fissure but slightly. The second slide has two branches for the first few hundred feet. Just north of No. 3 shaft, South Cliff, the lode is crossed by a strong zone of fissuring, which is represented on the maps as vertical. Little development work has been done south of this zone.

The mineralization was in the main confined to the fissure, though there was some mineralization of the amygdaloids. Here, as in the more productive part of the mine, the amygdaloids are closely spaced, and the old maps show no close relation between masses of copper and amygdaloids. Old reports speak of rich copper in the vein associated with the ninth and thirteenth floors, and on one of the old maps special mention is made of rich ground in the fissure where it intersects the thirteenth floor (just below the slide) from the 30-fathom to the 60-fathom level. In the lower levels, however, mineralization does not seem to have been strong in the thirteenth floor.

Mention is also made of rich ground where the fissure splits and includes a horse of the country rock. To the north the mineralization was limited by the slide. The vein passes through the Greenstone flow but has not been found to contain commercial copper there. The North Cliff workings are at the intersection of the fissure with the Ashbed amygdaloid. Here the vein is said to be a zone of fissuring 10 feet wide, but it contained relatively little copper.

No very clear description of the distribution of the copper in the fissure south from the Allouez slide has been found. The general impression gained from the old reports is that the vein was richest close to the Greenstone flow and grew leaner toward the south, and that the distribution was irregular, the richest portions being associated with the intersections of amygdaloids.

In some of the old reports the statement is made that the mineralization was cut off on the south "slide," and the maps show that very little stoping was done south of that slide. The vein may have about reached the limit of profitable working before passing the slide, and therefore it is not clear that the slide itself was an important factor in limiting the mineralization. The fissure and mineralization very evidently extended south of the slide. Exploration at No. 5 shaft, which is on the southern projection of the Cliff vein, has failed to disclose a strongly mineralized fissure.

Two possible causes for the richness of the fissure beneath the Greenstone flow have been suggested:

1. The fissure has been offset at the slide about 20 feet. If this offset occurred before mineralization, the interruption of the fissure and the presence of the gouge of the slide would form a barrier that might result in a concentration of solutions rising along it.

2. The area of greatest productivity is in a belt in which amygdaloids are very abundant, and there evidently was a relation between richness of the vein and some of the amygdaloids. The available description of the amygdaloids is too meager to judge of their character, but if there are several well-oxidized amygdaloids they might be an influential or even a controlling factor in the mineralization.

North Cliff.—The North Cliff Mining Co. was organized in 1858 to work the extension of the Cliff fissure above the Greenstone flow on lands set apart by the Pittsburgh & Boston Mining Co. The Cliff fissure had previously been traced by pits every few hundred feet from the most northerly Cliff shaft to the base of the Great conglomerate, a distance of 9,000 feet. In the Greenstone flow the fissure was found to be not more than 14 inches wide and to contain only a little copper. In the Ashbed lodes the vein was found broken into numerous branches for a width of 10 feet or more, and the branches were well filled with barrel and stamp copper. Three vertical shafts were sunk on the fissure near the Ashbed lode, one to the 30-fathom level, and an adit was driven south for more than 1,700 feet, cutting the Ashbed. The production to March 21, 1864, was 5,657 pounds of refined copper taken from the fissures as masses. An inclined shaft was also sunk on the Ashbed in or near the Cliff fissure, and some drifting was done on that lode, but there is no record as to the results obtained.

North American.—The North American Mining Co. worked for four years on a fissure under the Greenstone flow in the E. ½ sec. 2, T. 57 N., R. 32 W. The workings are on the north side of the North American gap, and the bearing of the fissure, N. 58° W., is such that it soon enters the gap. It was worked to a depth of 415 feet. The total yield was 445,000 pounds of refined copper. The fissure is split into three parts in the upper levels. There appears to be a difference of about 30° in the trend of the fissure and that of the gap.

Albion-Manhattan.—The Albion-Manhattan Co. in 1848 sunk a shaft 115 feet through the Greenstone flow, drove an adit to connect with it, and sunk 200 feet below the adit level. The vein was 2½ feet wide but barren. Later a shaft sunk to a depth of 70 feet j near the Greenstone flow yielded 5 tons of copper.

Mohawk.—-Several arsenide fissures have been prospected in the north end of the Mohawk mine. The main mineralized area is at the crossing of the Kearsarge lode and extends for a short distance into the hanging wall of the Kearsarge. A fissure opened south of No. 6 Mohawk shaft contained some copper near the intersection with the lode. The lode is also reported as rich near the fissure.

Fulton.—The Fulton fissure was opened in 1853 in the SW. ¼ sec 33, T. 57 N., R. 32 W. The vein was 18 inches wide. The same fissure has been opened in the North Ahmeek mine, where some masses of copper have been found, but as it is arsenical little has been mined. What seems to be the same fissure has been opened under the Greenstone flow. The vein material on the dump contains copper, but no record of the work has been found. The recorded production from this fissure by the Forsythe Mining Co. was 1,255 pounds, and some copper has also been produced by the Mohawk and Ahmeek mining companies.

Mass.—The Mass fissure of the Ahmeek mine where it crosses the Kearsarge lode strikes about N. 20° W. and dips steeply to the east. The fissure has been opened to the twenty-sixth level. Along the strike it has been developed to maximum distances of about 1,100 feet to the northwest from the Kearsarge lode and about 600 feet to the southeast. A slide fault intersects the fissure about 200 feet stratigraphically and 300 feet horizontally above the Kearsarge lode. The fissure, however, is not displaced. The fissure varies considerably in character from place to place. Commonly the fissure zone has a width of 2 to 4 feet, but it may pinch to a few inches or may spread to considerably more than the average width. Where the fissure zone is broad the rock within is sheared and brecciated.

Calcite is the most abundant vein mineral. Locally a foot or more of calcite occurs in the fissure. Quartz, epidote, prehnite, and laumontite are locally present. Copper occurs typically in large irregular more or less lenticular masses. In places there is a solid mass of copper a foot or even more in thickness in the vein. Some masses containing more than 200 tons of copper have been mined. Where the massive copper occurs the other vein minerals are usually sparsely represented. Chloritization is the most characteristic alteration of the wall rock and the breccia within the fissure, though there is some sericitization.

Most of the copper has been mined within 400 feet horizontally above and 200 feet horizontally below the Kearsarge lode. Copper is known to occur 1,000 feet from the Kearsarge lode, but the masses beyond 400 feet are small and scattering. Little copper has been mined above the ninth level. The general distribution of copper is shown in Plate 51. The Mass fissure to the end of 1925 is estimated to have yielded 11,567,000 pounds of copper.

Arsenide.—The Arsenide fissures in the Ahmeek, Mohawk, and Seneca mines have the same general dip and strike as the Mass fissure. They have been developed but a short distance away from the Kearsarge lode. The principal vein minerals are quartz, calcite, ankerite, and the copper arsenides. Albite, prehnite, and laumontite are present in variable amounts. The typical rock alteration associated with the Arsenide fissures is chloritization and sericitization. In places the veins contain a foot or even more of nearly solid copper arsenides at their intersections with the Kearsarge lode, but there has been little production from these veins.

Minesota and Branch fissures and Calico lode.—The occurrence of the ore in the Calico lode of the Minesota mine is closely associated with that in the fissures, and they are therefore described together. The statements here given are based on old descriptions and company maps and records, as there was no opportunity for underground examination. The copper occurs mainly in two northward-dipping beds and in strike fissures that parallel the beds or dip more steeply than the beds and cut them. The lower bed, the Minesota conglomerate (South Branch) is about 125 feet below the Calico amygdaloid (North Branch). Striking nearly parallel with the beds is the Branch fissure (Middle Branch), which cuts both the Minesota conglomerate and the Calico amygdaloid. The Minesota fissure is represented as diverging from the Branch fissure where the latter cuts the Minesota conglomerate and as following the top of the conglomerate to the outcrop. The operations on the Minesota fissure (pl. 52) were among the earliest and have been the most profitable in Ontonagon County. No separate record of the copper from the Minesota and Branch fissures and Calico lode is available, but most of the output came from the Minesota and Branch fissures. Production began in 1848. To 1880 a total of 53,000,000 pounds of copper was produced from the Minesota, National, and Rockland mines, and dividends of $2,140,000 were paid.

The Michigan Copper Mining Co., began operations in 1899. From 1899 to 1912 the Calico lode and the Branch vein were rather extensively opened and mined. The Branch vein was apparently the most productive. A total of 17,180,000 pounds of copper was produced. The yield from the stamp rock probably did not exceed 12 pounds to the ton, but there was much mass copper, especially on the Branch vein.

Production and dividends from Minesota and Branch fissures and Calico lode

Mine	Period	Copper produced (pounds)	Dividends: Total	Dividends: Per pound of copper (cents)
Minesota	1848–1885	34, 707, 000	$1, 820, 000	5. 24
National	1853–1895	11, 613, 000	320, 000	2. 67
Rockland	1854–1880	5, 821, 000		
Branch	1902–1912	[a] 9, 174, 000		
Calico lode	1900–1913	[a] 8, 006, 000		
		69, 321, 000	2, 140, 000	3. 00

[a] Estimated.

The Minesota conglomerate is a few hundred feet above the Evergreen and succeeding lodes, and the Calico amygdaloid is about 125 feet above the Minesota conglomerate. Next above the Calico lode is the North lode, on which some development work has been done. The beds dip 47°-50° N., steepening slightly with increased depth and toward the southwest. Striking approximately with the beds but dipping at a steeper angle is the Branch vein or fissure. The outcrop is mainly in the hanging wall of the Calico lode except between shafts A and B. At shaft B the Branch vein is represented as diverging from the Calico lode above the fifth level and entering the conglomerate between the thirteenth and fourteenth levels. The dip varies considerably from place to place. At the contact with the conglomerate the Branch fissure is represented as splitting off from the South or Minesota fissure, which is shown as following the hanging wall of the conglomerate to the outcrop. There was apparently little displacement of the beds on the Branch fissure, though in places at least there seems to have been much shattering of the rock. Other fissures are mentioned in the records but do not seem to have been of great importance.

The Minesota conglomerate where seen on the outcrop is a pebble to boulder conglomerate composed mainly of felsitic material and similar to the other felsitic conglomerates of the area. In some sections it is represented as 25 feet thick and underlain by nearly as much sandstone, though it doubtless varies in thickness and averages less than 25 feet.

The Calico lode is apparently a fragmental lode varying in thickness and in character from place to place, as is characteristic of the fragmental lodes in general.

The Minesota fissure follows the hanging wall of the Minesota conglomerate from the outcrop to its intersection with the Branch fissure. The copper occurred characteristically in masses, some of great size. One mass of 527 tons, the largest ever found, was taken out in 1856. The masses are said to have occurred both in the fissure and in the underlying conglomerates. Apparently much of the copper replaced conglomerate but was closely associated with the fissure. Where seen on the dump the copper-bearing conglomerate shows the bleaching by removal of iron characteristic of conglomerate mineralization elsewhere. The Minesota fissure was productive from the surface to about the 140-fathom level. Beyond the junction of the Branch fissure it appears to have been poor, at this junction and those of minor fissures it was apparently rich.

The developments on the Calico amygdaloid by the Michigan Copper Mining Co. showed the best ground to be at and above the intersection with the Branch fissure, especially in shafts A and B. There was some fair ground reported below the intersection in shaft C, but not much was stoped. The Calico lode yielded little mass copper, the output being mainly stamp rock.

The Branch fissure was mined by the Michigan Copper Mining Co. nearly to the intersection of the Minesota conglomerate between shafts B and C, but at the intersection it was said to be lean. It is not clear from the descriptions whether the fissure continued on its normal dip through the conglomerate or flattened into the dip of the conglomerate. The copper occurred mainly as mass copper, but there was considerable production from stamp rock.

Norwich.—The Norwich mine, 8 to 10 miles southwest of the Victoria mine, was productive intermittently from about 1852 to about 1870. The records show an output of 993,360 pounds of copper. The operations were mainly on fissures crossing the beds. The fissures contained some large masses of copper, but considerable rock was also milled. The fissures are described as quartz-epidote veins. The Norwich property was later explored by the Cass Copper Co., mainly by diamond drilling. Northeast of the Norwich mine there were some early operations on fissures, but apparently little copper was produced.

LARGE-SCALE MAPS AND GEOLOGIC SECTIONS

The surface maps of the district were prepared on a scale of 1 inch = 500 feet. A small edition of these maps was published in 1925. The cross sections were prepared on a scale of 1 inch = 200 feet. Part of them were prepared on tracing cloth and can be reproduced by blue printing. It was not found feasible to publish the detailed descriptions of sections, but two copies of such records have been prepared.

The original plates of the large-scale surface maps and of the cross sections have been deposited with the Michigan School of Mines and Technology at Houghton, together with one copy of the description of geologic sections. A second copy of the description of geologic sections has been deposited in the Calumet & Hecla library at Calumet. A few copies of the large-scale maps are available for distribution by the United States Geological Survey.

ADDENDA TO BIBLIOGRAPHY

The following entries were obtained after this report was in page proof:

BALDWIN, C. KEMBLE.

Tailings disposal plant at the Wolverine mill: Eng. and Min. Jour., vol. 88, pp. 71-73, 1909.

BLAKE, WILLIAM P.

The mass copper of Lake Superior mines and the method of mining it: Am. Inst. Min. Eng. Trans., vol. 4, p. 110, 1876.

BRODERICK, THOMAS MONTEITH, and HOHL, C. D.

Geophysical methods applied to exploration and geologic mapping: Econ. Geology, vol. 23, pp. 489-514, 1928,

CAMPBELL, A. C.

The copper and iron bearing rocks of Lake Superior: Eng. and Min. Jour., vol. 31, pp. 20-21, 1881.

COOPER, JAMES B.

The history of copper smelting in the Lake Superior region: Eng. and Min. Jour., vol. 71, pp. 529-530, 1901.

CRANE, W. R.

Drilling practice in the Lake Superior copper mines; Drifting and stoping at Lake Superior; Underground ore handling at Lake Superior; Shaft sinking at the Wolverine mine; Ore breaking at Lake Superior; Mine timbering at Lake Superior: Eng. and Min. Jour., vol. 82, 1906.

EDWARDS, G. E.

The Quincy mine, Michigan, from stope to smelter: Min. and Eng. World, Apr. 20, 1912.

FRASER, LEE.

Practice at the Osceola mill, Lake Superior: Eng. and Min. Jour., vol. 83, pp. 1180-1183, 1907.

HODGE, WALTER R.

The Ahmeek mill, Hubbell, Mich.: Eng. and Min. Jour., vol. 94, pp. 749-571, 1912.

HORE, REGINALD EDWIN.

Methods of prospecting and developing deposits in Michigan: Canadian Min. Jour., Jan. 1, 1913.

HOUGHTON, JACOB, JR.

Early history of the mineral region of Lake Superior: Am. Min. Jour, and Railroad Gazette, vol. 1, pp. 57-59, 1847.

LOWE, FRANCIS A.

The Silver Islet mine and its present developments: Eng. and Min. Jour., vol. 34, pp. 320-323, 1882.

MOFFETT, S. E.

Romances of the world's great mines, III, Calumet & Hecla: Cosmopolitan, April, 1903.

PAINE, RALPH D.

The story of a copper mine: Outing, June, 1907.

RICE, CLAUDE T.

Baltic method of mining: Eng. and Min. Jour., vol. 93, pp. 843-847, 1912; Sinking the Hancock No. 2 shaft: Eng. and Min. Jour., vol. 95, pp. 787-791, 1913.

ROLKER, CHARLES M.

The Allouez mine and ore dressing, as practiced in the Lake Superior copper district: Eng. and Min. Jour., vol. 23, pp. 274-275, 294-296, 314-315, 335-336, 1877.

SINGEWALD, JOSEPH T., JR.

Genetic comparison of Michigan and Bolivian copper deposits: Econ. Geology, vol. 23, No. 1, pp. 55-61, 1928; Review of "Beiträge zur Frage der Entstehung der Balimanischen Kupferzlagerstatten vom Tyrus Carico," by Bruno Geier (Neues Jahrb., Beilage-Band 58, pp. 1-42, 1927): Econ. Geology, vol. 23, pp. 583-584, 1928.

SKEWES, EDWARD.

Electric ore-finding system: Eng. and Min. Jour., vol. 75, pp. 780-782, 1903.

STONE, CHARLES J.

Lode copper mining on Keweenaw Point, Michigan: Min. World, October, 1908.

WINCHELL, NEWTON HORACE.

Ancient copper mines of Isle Royal: Eng. and Min. Jour., vol. 32, pp. 184-186, 201-202, 1881,