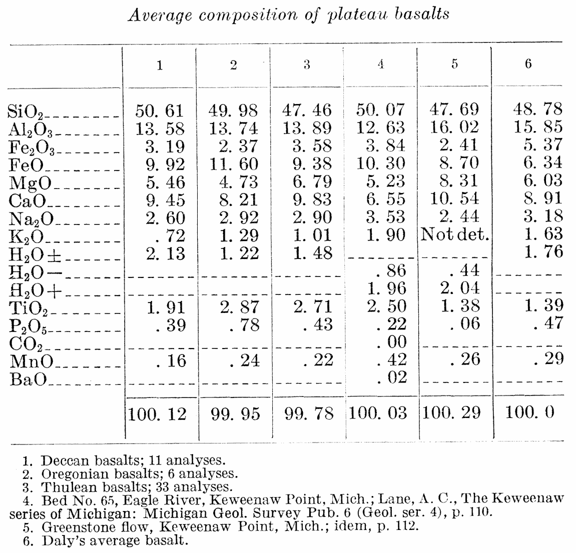

Average composition of plateau basalts

	1	2	3	4	5	6
SiO_2	50. 61	49. 98	47. 46	50. 07	47. 69	48. 78
Al_2O_3	13. 58	13. 74	13. 89	12. 63	16. 02	15. 85
Fe_2O_3	3. 19	2. 37	3. 58	3. 84	2. 41	5. 37
FeO	9. 92	11. 60	9. 38	10. 30	8. 70	6. 34
MgO	5. 46	4. 73	6. 79	5. 23	8. 31	6. 03
CaO	9. 45	8. 21	9. 83	6. 55	10. 54	8. 91
Na_2O	2. 60	2. 92	2. 90	3. 53	2. 44	3. 18
K_2O	. 72	1. 29	1. 01	1. 90	Not det.	1. 63
$H_2O\pm$	2. 13	1. 22	1. 48	-------	-------	1. 76
H_2O-	-------	-------	-------	. 86	. 44	-------
H_2O+	-------	-------	-------	1. 96	2. 04	-------
TiO_2	1. 91	2. 87	2. 71	2. 50	1. 38	1. 39
P_2O_5	. 39	. 78	. 43	. 22	. 06	. 47
CO_2	-------	-------	-------	. 00	-------	-------
MnO	. 16	. 24	. 22	. 42	. 26	. 29
BaO	-------	-------	-------	. 02	-------	-------
	100. 12	99. 95	99. 78	100. 03	100. 29	100. 0

1. Deccan basalts; 11 analyses.
2. Oregonian basalts; 6 analyses.
3. Thulean basalts; 33 analyses.
4. Bed No. 65, Eagle River, Keweenaw Point, Mich.; Lane, A. C., The Keweenaw series of Michigan: Michigan Geol. Survey Pub. 6 (Geol. ser. 4), p. 110.
5. Greenstone flow, Keweenaw Point, Mich.; idem, p. 112.
6. Daly's average basalt.

The Greenstone flow (No. 5) is an olivine basalt; the Eagle River rock (No. 4) is more feldspathic but clearly of basaltic type.

TEXTURAL TYPES

The one outstanding characteristic of the flows that is most useful in their classification is their texture, which serves as one of the major bases of correlation from section to section. Textural classification may be made in hand specimen, drill core, or outcrop and gives to some extent an indication of the variation in chemical composition. Lane has distinguished four general types—ophite, melaphyre, porphyrite, and glomeroporphyrite. The many variations of these types, which, indeed, grade into one another, are designated by modifying adjectives, such as feldspathic. Lane also recognizes dolerites, which are a coarse or pegmatitic facies of any of the others.

There may be differences of opinion as to the appropriateness of the names used in this classification, but to anyone who has examined drill cores from this series of rocks there can be no doubt as to the usefulness of the distinctions. The textural features that have been emphasized come out very strongly on the ground surface of drill cores, as can be seen by reference to Plate 56. Lane's classification has therefore been used in the maps and sections accompanying this report.

Ophite.—Ophitic texture is the roughly circular mottling of the rock produced by crystals of pyroxene that surround and inclose the feldspar crystals (pls. 56, 57). The ophitic lavas are the "luster-mottled melaphyres" of the earlier publications on the district. The size of the pyroxene crystals varies with their distance from the contact of cooling and somewhat with the composition of the lava. Lane[23] has given an exhaustive discussion of this subject and its application, which need not be repeated here. Roughly he finds that the size of the pyroxenes increases 1 millimeter for each 8 to 10 feet of distance from the upper or lower contact of the flow. It is needless to say that this fact is of great value in studying the flows having ophitic texture. In some of the thick flows, like the Greenstone flow", the crystals are 2 inches and more in diameter, and their outlines are not readily traced in the ordinary sized drill core, but they are conspicuous on a weathered surface, where the centers stand up as knobs, and in freshly broken rock they can be seen by the Hashing of cleavage faces.

Where inclusions have been dragged into a flow the mottling around them is finer than elsewhere at a corresponding distance from the surfaces of the flow. This may account for some of the ophites of varying or banded mottling.

Porphyrites.—The porphyrites are rocks that contain well-defined crystals, usually of feldspar, of an older generation than the same mineral in the ground-mass.

Glomeroporphyrites.—In the glomeroporphyrites the feldspars show a considerable variation in size, though not so definite a difference in size and time of formation as is shown between the feldspar phenocrysts and the ground in ass feldspars in the porphyrites. The larger feldspars are collected into bunches or clots.

Melaphyre.—Melaphyre is a term applied to rocks that show none of the distinctive textures indicated above. Many beds that show a distinctive texture near the center lose it near the margins, and many thin flows do not show a distinctive texture in any part. There are also some flows 100 feet or more in thickness that show no distinctive texture and are classed as melaphyre.

Dolerite.—The term dolerite is used to designate portions, in the lavas of certain types, in which the minerals, especially the feldspars, are unusually coarse and the rock has a pegmatitic texture. Rock of this type occurs in the thicker beds and is regarded as portions that crystallized late. It is allied to the pegmatite facies of some intrusive rocks. The term dolerite has been used by some petrographers in a different sense.

RELATION OF TEXTURE TO COMPOSITION

The ophitic texture is best developed in the more basic lavas, where it is conspicuous even in the thin flows and very near to the margin of the thick flows. In the more feldspathic lavas the ophitic texture may be conspicuous near the center of thick flows but absent from the thinner flows and near the margin of the thicker flows. The porphyritic and glomeroporphyritic textures are characteristic of the more feldspathic beds or those approaching andesite, though phenocrysts are present in some ophitic flows, as the Kearsarge flow, in which they are especially abundant just below the amygdaloidal top.

The melaphyre texture, as already indicated, is found in the less basic beds. The feldspathic beds in the south

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[21] Aldrich, H. R., Econ. Geology, vol. 18, p. 570, 1923.

[22] Washington, H. S., Deccan traps and other plateau basalts: Geol. Soc. America Bull., vol. 33, pp. 774, 779, 789, 1922.

[23] Lane, A. C., Michigan Geol. Survey Pub. 6 (Geol. ser. 4), vol. 1, p. 145, 1911.

end of the district show no definite texture and are of the melaphyre type.

DISTRIBUTION OF THE DIFFERENT ROCKS

Most parts of the section are characterized by the predominance of one or another of these textural types, which were produced by recurrences of different phases of the eruption of lava.

Below No. 6 conglomerate (see pl. 15) the flows are prevailingly ophites, commonly of the banded type. For a few hundred feet below and several hundred feet above No. 8 conglomerate, glomeroporphyrites and melaphyres predominate, especially from Portage Lake north to Keweenaw County. The series of thin beds above No. 8 conglomerate are typically glomeroporphyrites. Between the Kearsarge conglomerate and the “Mesnard” epidote the flows are typically ophites, and above the “Mesnard” glomeroporphyrites and melaphyres prevail. The flows above the Great conglomerate and below the Outer conglomerate—the Lake Shore trap—are melaphyres. Commonly there is a transition zone of varying width between the flows of different types, in which the rock is intermediate and more variable in composition.

In the south end of the district the “Chippewa” felsite, a siliceous rock of rhyolitic composition, forms a continuous belt in the upper part of the lava series and also crops out in the central area of the Porcupine Mountains. This rock is similar in composition and character to some of the felsite intrusives, and its presence in the center of the Porcupine dome therefore naturally suggested, to Irving and those who have studied it since, the possibility that it is intrusive and that the dome is of laccolithic origin. That there are intrusive rocks in this area is known, but those who have studied the felsite have regarded it as an effusive which has been domed with the other rocks and have correlated it with the “Chippewa” felsite belt to the south.

CHARACTER OF ERUPTIVE ROCKS

The Keweenawan flows clearly belong to the type of volcanic accumulation known as plateau or fissure flows, which are recognized in many parts of the world. Washington[24] has recently summarized the characteristics of this type of flow in a paper from which the following passage is quoted:

> In various parts of the earth and at different geological horizons are large areas covered by very extensive, generally horizontal series of sheets of basaltic lavas, the series of overlying flows often attaining thicknesses of thousands of meters. In some cases they are accompanied by flows of rhyolite. These basalts have poured out in an evidently very fluid condition, as they occupy preexisting valleys and cover the lower topographic features much like floods of water, the separate flows being very long—many of them measured by miles.
>
> It is generally assumed by volcanologists that these extensive, horizontal, very fluid flows have issued quietly from Assures—an idea first suggested by Sir Archibald Geikie.[25] Volcanic cones, formed of lavas, ashes, or both, are present in places, but these are inconspicuous, being low because of the fluidity of the lavas, and they always form a very minor feature of the complex.
>
> Such lavas are called variously “fissure” or “plateau” flows. The term “plateau” is used here because the word “fissure” connotes the mode of origin, which is still somewhat uncertain.
>
> *   *   *
>
> It is well known that the lavas of these plateau eruptions are mostly basalt, and this petrographical character is the usually accepted explanation of the great extension and horizontality of the sheets, since basalts generally are known to be notably fusible at a lower temperature and more fluid when fused than are more silicic lavas. But basalts vary much, both chemically and modally, and many of them are evidently, on extrusion, less fluid than are those of the plateaus. This is especially true of the basalts of many volcanoes of the explosive type, the flows of which do not extend very far and are often found consolidated on steep slopes, as was pointed out nearly 100 years ago by Lyell.

After discussing the Deccan, Oregonian, Thulean or northern Atlantic, Siberian, Patagonian, Algonkian (Keweenawan), and Palisades (New Jersey) regions, Washington reaches the following conclusions:

> We may now summarize the general characters of the plateau basalts. Structurally, they have characteristically issued from fissures, although this quiet extrusion is sometimes accompanied by minor explosive activity. They form horizontal flows of very great extent, indicating a high degree of fluidity at the time of extrusion. The flows are individually of considerable thickness, and the total thickness of the series of superimposed flows is very great. Ash beds and layers of scoria are not abundant. In several regions the basalts are associated with flows of rhyolite or toscanite, while accompanying andesite and trachyte are rarely met with, and lenadic lavas, such as phonolite or tephrite, seldom or never occur. They have been extruded at very different geological epochs, from the pre-Cambrian to recent times.
>
> Megascopically, they are very dark, black or occasionally brownish black, rarely dark gray. In granularity they may vary from rather coarsely doleritic to densely aphanitic, some few being evidently highly vitreous. Vesicular forms seem to be rare as compared with ordinary basalts of volcanic cones. The great majority are aphyric, but there is some tendency to a porphyritic development of the feldspar, especially in the Thulean region, forming a special textural type. Augite seldom forms megaphenocrysts, and these small and sparse, while olivine phenocrysts are very rarely present, except in some of the Algonkian and Palisadan [Triassic] diabases.   *   *   *
>
> Chemically, the plateau basalts differ materially from other basalts in one or two features. In the table are given the averages of analyses of basalts of various regions, with the average basalt as computed by Daly from 161 analyses of basalts so named by the authors.[26] [See p. 23.]
>
> The averages of the three most typical plateau basalt regions—the Deccan, Oregonian, and Thulean—are closely alike. * * * The chief difference is seen in the much higher amount of iron oxides, with ferrous oxide greatly preponderating over ferric oxide. In the typical plateau basalts the combined iron oxides would amount to about 14 per cent or more, and this is the more marked if only the most abundant

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[24] Washington, H. S., Deccan traps and other plateau basalts: Geol. Soc. America Bull., vol. 33, pp. 765-804, 1922.

[25] Nature, November 4, 1880.

> group of the more femic basalts are considered. I am inclined to think that the comparatively high ferric oxide shown in Daly's average is due in part to oxidation of ferrous oxide through slight alteration and in part to defective determination of the ferrous oxide—a not unusual analytical error. The percentage of titanium dioxide is appreciably high in the plateau basalts.
>
> It would thus appear that the plateau basalts differ from what might be called the cone basalts essentially in the higher iron and titanium content of the former and possibly in the relatively less oxidized condition of the iron. This must be considered as a broad general distinction. Examples may be found among typical plateau basalts in which the iron oxides are not specially high, just as examples may be found among cone basalts in which the iron oxides are much higher than the average. Mineralogically, as we have seen, this chemical difference is expressed in the presence of highly ferromagnesian hedenbergitic enstatite-augite in the plateau basalts, in contrast to that of highly calcic or diopsidic augite in the cone basalts. It may also find expression in the striking tendency of the augite and magnetite to be among the last minerals to crystallize; so that the glass present in the not wholly crystallized plateau basalts would have a composition corresponding to a mixture of augite and magnetite, examples of which we have seen on the island of Skye, in Colorado, and possibly elsewhere.
>
> The preceding descriptions of the plateau basalts, showing that one of their main chemical characteristics is the high percentage of iron oxides, and especially of ferrous oxide, furnish an explanation of their great fluidity at the time of extrusion. It is a matter of common observation that basalts generally are fusible at a lower temperature and are more fluid when molten than are more feldspathic or more silicic rocks. It is also well known that ferrous silicates are more readily fusible than are magnesium or calcium silicates. The experience of iron and steel workers and smelters bears testimony to the lower fusibility and greater fluidity of slags containing considerable iron. * * *
>
> Inasmuch as the fissure eruptions which furnished the plateau basalts show slight explosive activity, it is to be inferred that the magma contained comparatively little gas, so that the effect of this class of components in lowering the fusing point or increasing the fluidity should be less than in ordinary basalts of the explosive cone type. We seem, therefore, to be justified in ascribing the peculiar physical condition of these basalts during their extrusion chiefly to their high iron content.

It is clear that the Keweenawan flows belong with the plateau type, that they were probably erupted from fissures, and that they were highly fluid, forming sheets of nearly uniform thickness over large areas, a feature in which they approach sedimentary formations. Whether their great fluidity was due primarily to the high iron content, to a high initial temperature, to high gas content, or to a combination of these conditions is not so clearly established.

LOCATION OF VOLCANIC VENTS

Although it seems likely that the flows issued from fissures, there is no positive evidence to indicate where these fissures were located. It has been suggested that the Keweenawan dikes, which, as Van Hise and Leith[27] point out, practically surround Lake Superior, fill the fissures through which the lavas issued. The same authors consider it possible that similar vents may underlie Lake Superior. The presence of deep-seated intrusive rocks near the Keweenaw fault has led Lane[28] to believe that the fault is possibly the fissure through which the lavas poured. Hotchkiss[29] believes that fissures centralized within the Lake Superior basin were of chief importance as lava vents and cites evidence to support this view.

The work on which this report is based has added little positive evidence of the direction of flow of the lavas. The "pipe" amygdules, however, which have been formed at the base of some of the flows, are in places bent away from the basin, or up the present dip, suggesting a flow from the north or from some locality within the basin. The Calumet & Hecla conglomerate also thickens down the dip, and the cross-bedding in places suggests currents from down the present dip. Both these facts seem to indicate that the lavas came from the north.

As is pointed out in the discussion of structure (p. 50), there is reason to believe that the Lake Superior basin was being formed while the lava series was being built up. The filling of the basin could have been accomplished either by lava flowing into the basin from the rim or by lava issuing from fissures within the basin. If Lane is correct in correlating beds on opposite sides of the basin, it would perhaps be more likely that the lava flowed outward both north and south from vents within the basin than that it originated on one side, filled the basin, and then extended completely across.

AMYGDALOIDS

Each flow is made up of two major parts, which grade into each other. The larger part in most flows, especially in the thick ones, is a massive rock, varying, principally in texture, from center to bottom and top. This is the trap portion. The top of the flow, usually to a depth of several feet, is porous and cellular. This is the amygdaloid portion. There is usually an amygdaloid portion at the base also, but as a rule it is only a few inches in thickness.

TRAP

The trap makes up 80 to 90 per cent of the total thickness of the thicker flows but constitutes a smaller proportion of the thinner flows. It is a dark-gray or greenish-gray rock, ordinarily of rather uniform appearance except for grain. It is commonly much cut by joints of varying directions, which cause it in mining to present blocky, angular surfaces that serve to distinguish it, even on dust-covered faces, from the "shorter " or more granular fracture of the amygdaloid. Only in the Greenstone and a few other flows, and there crudely,

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[26] Daly, R. A., Am. Acad. Proc, vol. 45, p. 224, 1910.

[27] Van Hise, C. R., and Leith, C. K., U. S. Geol. Survey Mon. 52, p. 411, 1911.

[28] Lane, A. C., Unexplored parts of Keweenaw Point: Lake Superior Mm. Inst. Proc, vol. 17, p. 135, 1912.

[29] Hotchkiss, W. O., The Lake Superior geosyncline; Geol. Soc. America Bull., vol. 34, pp. 669-678, 1923.

has the columnar jointing so common in basalts been observed.

As has been noted generally in other regions and emphasized particularly by Lane for this region, the top and bottom portions of the trap are likely to be of finer grain than the middle portion. This variation in size of grain, especially in the ophites, may be so constant that it is possible to determine approximately the distance of a specimen from the margin of the flow by determining its average size of grain. As a rule, the thicker the flow the coarser the texture of its middle portion; in the Greenstone flow, for instance, the coarsest material is composed of grains 2 inches or more in diameter. In many of the coarser-grained flows, the presence of large crystals of pyroxene with included feldspar crystals gives the peculiar spotted appearance that characterizes Pumpelly's "luster-mottled melaphyre" and Lane's "ophite." A notable variation within some of the thicker flows is afforded by lenses of coarse pegmatitic material rich in feldspar and frequently in iron oxide which Lane has called "doleritic" bands. These are present in the Greenstone flow and other large "ophites" but are more abundant in the more highly feldspathic flows. The trap of certain flows, notably those in the Ashbed group, contains small laths or plates of lighter-colored feldspar scattered more or less sparingly through the fine-grained groundmass.

In some flows and possibly in all there is a slight tendency toward the concentration of more basic material near the bottom by settling. At the base of the amygdaloid of the Kearsarge flow there is a zone from a few inches to several feet thick containing abundant feldspar phenocrysts that collected by rising from the underlying lava. But such evidences of gravitative segregation are relatively inconspicuous. The most noteworthy chemical variation in the flows is an increase in ratio of ferric to ferrous iron from bottom to top. This feature is discussed on page 34.

In the early days, before the true character of the rocks had been ascertained, the "amygdaloid" and the "trap" were not recognized as parts of a single geologic unit but were regarded as independent bodies, and a more definite distinction was accordingly made between them than would be made now. The commercial importance of the amygdaloid as contrasted with the trap has, however, caused this distinction to survive long after the geologic relation of the two had been recognized, and even now there are many who do not clearly realize that a given layer of amygdaloid is any more closely connected to the underlying trap than to the overlying one. The trap represents that portion of the flow from which the gas had escaped before consolidation and crystallization of the rock took place; the amygdaloid represents the upper bubbly or frothy crust in which the rising gas bubbles were frozen before they could escape because the top of the flow consolidated more quickly than the main portion underneath. The thin amygdaloid layer at the base of a flow was likewise produced by the freezing-in of gas bubbles.

BOTTOM AMYGDALOID LAYER

Many descriptions of flowing lava refer to the continual falling down of solidified lava blocks and fragments over the advancing front of the flow, which overrides and buries them. This would imply that at the bottom of the flow there should be found an accumulation of fragmental material of the same nature as that which makes up the brecciated tops; indeed, some descriptions mention the fragmental layers at both top and bottom of flows. In the Michigan lavas no such fragmental material is consistently present at the bottoms of the flows. Examination has been made of the bottoms of many flows, including some of both the smooth-top and the brecciated or rough-top types, without revealing fragmental material that has been clearly rolled under. At the bases of some flows that rest on sedimentary rocks, however, a few feet of amygdaloid is found in some places. As this basal amygdaloid is particularly well developed in flows resting on sediments and in its stronger development has not been noted in flows resting directly on other flows, it seems more likely that it has resulted from some characteristic of the underlying bed—water content, for example— than from material rolled under the advancing flow. No evidence has been seen to indicate that fragmental material that may have been rolled under the flow was either remelted or was floated up into the flow. The same statement applies to the material of the underlying bed. All the evidence indicates that the bottom froze very quickly, though where a flow covered very open-textured material the lava filled the spaces between the fragments for a short distance below the surface. This is especially noticeable where a flow covered coarse trappy fragmental amygdaloid.

Characteristically the basal amygdaloid consists of a lower layer of finely amygdular rock, usually not more than an inch in thickness, and an overlying layer containing larger amygdules, which in some places are elongated upward and are then called "pipe" amygdules. This second layer is commonly only 2 or 3 inches thick but may be a foot or more, and the pipe amygdules range from a fraction of an inch to more than 6 inches in length. The pipe amygdules are not strongly developed in all flows. They are well shown at some places in the flows that overlie the Kearsarge flow, the Calumet & Hecla conglomerate, and the Pewabic lode and in certain flows in the Mayflower-Old Colony mine. Other flows, as those above the Osceola, Isle Royale, and Baltic lodes, show very little basal amygdaloid.

Usually the pipes extend upward perpendicular to the underlying surface, but at some places in the flow above the Calumet & Hecla conglomerate and in the Mayflower-Old Colony mine the upper parts of the pipes are bent over in a common direction which is believed to be the direction of flow. The basal amygdaloid above some sedimentary beds may reach a few feet in thickness and be distinctly fragmental.

The evidence seems to indicate that the basal amygdaloid was formed by the rapid cooling of the lava in contact with the underlying rock. The thin layer immediately above the cooler rock solidified very quickly, and the gas liberated from the lava was entrapped as small bubbles. Above this bottom layer there was more time for the gas bubbles to collect and coalesce, and much larger ones were formed. Under certain conditions these bubbles expanded upward into the less viscous lava, forming the pipe-shaped cells which, when later filled with minerals, became pipe amygdules. The fact that the basal amygdaloid is more strongly developed above sedimentary beds than above other flows suggests that the gas that filled the cavities may have been in part derived from the underlying material and also that the sedimentary beds contained more water than the flows. Such water was converted to steam and absorbed by the overflowing lava and was thus a factor in the formation of the basal amygdaloid.

The thinness or absence of basal amygdaloid in some flows may mean that the lava flowed over a surface not yet cooled and that solidification was slow enough to permit the gas to escape before the lava became sufficiently viscous to retain it as bubbles.

THE LAVA TOPS

VARIETIES

The copper derived from the amygdaloidal tops of the lava flows has amounted to nearly half the total production from the region and now exceeds that from conglomerate lodes and fissures combined. The greatest part of this production from amygdaloids has come from only six flows of the scores that are present. It is essential, therefore, that the character and method of origin of these upper parts of the flows be understood if a clear idea is to be gained of the conditions that determined the deposition in them of commercial ore.

The tops of lava flows have long been divided by geologists into two general types—smooth tops and rough tops—to which the native Hawaiian names, respectively “pahoehoe” and “aa,” are commonly applied. The smooth tops are highly vesicular or cellular; the rough tops less so. Both types are plentifully represented by the Keweenawan flows, and the differences between them are such as to affect materially the ease of copper deposition in them. The smooth tops may be further divided into normal vesicular tops and coalescing vesicular tops; the rough tops are separable into fragmental or brecciated tops and scoriaceous tops. (See pls. 58-61.)

In their typical development the different types of tops are perfectly distinct in character, but there are all gradations between the different types in different flows and between most of the types in some single flows. Thus the Kearsarge lode has in some places a typical cellular top, in others a well-developed fragmental top. The same is true of some of the Pewabic flows. The Ashbed flow is typically scoriaceous but locally fragmental. Many flows, however, have a tendency to be either cellular or fragmental over long stretches. The tops of the thin series of flows above No. 8 conglomerate are rather typically cellular. The Osceola flow and other flows have fragmental tops for many miles. The thickness of the flow does not seem to control the character of the top. Many of the thin flows have cellular tops, but the tops of thick flows may be either cellular or fragmental. More of the fragmental tops occur, however, on thick flows, though there are numerous examples of fragmental tops on relatively thin.

The differences between the rough and the smooth tops go far beyond mere difference in texture of surface; the smooth tops approach much more nearly a plane surface, but the rough tops were hummocky and irregular, with differences in altitude of probably 30 feet. This difference is brought out strikingly in the drifts that follow the tops of the flows. In the Pewabic lode, a smooth-top flow, the drifts are essentially straight for hundreds of feet, but in the Osceola lode, a rough-top flow, they are exceedingly irregular.

SMOOTH TOPS

The most notable differences in the smooth tops arise from the size and distribution of the gas bubbles or vesicles, now chiefly filled with minerals to form amygdules. In the prevailing class of smooth tops the vesicles are abundant, of moderate size, and arranged more or less definitely in layers parallel to the surface of the flow, so that the rock commonly has a banded appearance. Generally the amygdules are small and abundant near the top and increase in size and decrease in number deeper in the flow. The layers may be closely spaced or may be separated by layers of rock containing relatively few amygdules, several times as thick as the diameter of an average amygdule. Irregular spacing of the layers is the rule, though in places in the Pewabic lode (see pl. 56) there is an approach to regular spacing. The individual vesicles are for the most part not spherical but flattened in the plane of the flow, some being decidedly elongated and a few showing a tendency to be flatter on their upper side.

The distribution of the vesicles in layers and the elongation of the vesicles in the plane of the lode have commonly been ascribed to flow movement in the lavas. It seems likely that the banding in the Michigan flows may be explained as follows: A period in which many rising gas bubbles collected under a solidified surface was followed by a period of relatively rapid consolidation when few bubbles collected, and this In turn by another period when many bubbles collected, and so on till a depth was attained where the gas was not present in sufficient quantity to form vesicles. The amygdules are fewer and the banding less distinct near the base of an amygdaloid. A similar grouping of vesicles is present in slags solidified in pots where there is no flow movement of the liquid.

The individual bubbles in a layer may be separated by rock stuff exceeding their own diameter, or they may be so closely spaced that two or more adjacent ones may coalesce into a unit that is of irregular shape because the lava had become too viscous to permit the enlarged bubble to assume the usual rounded form. In this way some extremely irregular amygdules may result, and those that are large and conspicuous, as in places near the bottom of the vesicular zone, constitute what Pumpelly and Marvine called “pseudo-amygdules,” on the assumption that they were formed chiefly by replacement of rock rather than by filling of gas cavities. Some amygdules were slightly enlarged by replacement, but there is little to suggest that this process took place generally or on a large scale.

Rarely if at all in this or in any of the other types of tops is the degree of vesiculation such as to justify the term pumice. A structure more like that of Swiss cheese is the common one.

Permeability is the quality of the amygdaloid tops that makes them more receptive to copper deposition than the traps. The cellular or banded vesicular rock of the smooth-top flows is more permeable than nonvesicular rock, such as the underlying trap, for the reason that in a given volume of it only part is solid rock. A rock in which the vesicles make up 50 percent by volume would have twice the permeability of otherwise similar but nonvesicular rock. But this cellular rock has no through-going and continuous openings, such as would be favorable to high permeability; instead, each opening is of small extent and is walled off from other openings by solid rock. The difference in permeability between the cellular tops and the brecciated tops is therefore very great, and for this reason the smooth tops of the normal sort contain little copper as compared to the rough tops. A subdivision of the cellular type of smooth lava top is recognized in which the individual vesicles are much larger, reaching an inch or more in diameter, at least in certain layers. Many of these vesicles in the same layer coalesce into a thin, jagged gash that may attain a lateral extent of as much as 10 or 12 feet in a single cross section and perhaps form a connected opening for scores of feet in the plane of the flow. Rock containing these openings may be called a coalescing top, or “lode.” A series of such openings with little rock material between may constitute almost unbroken openings for long stretches along the plane of the flow. Several such open layers may occur in the same flow top. Where the degree of coalescing of the vesicles is less than that just described, the large vesicles, now filled with minerals, may be closely spaced like beads on a string.

The cause of this coalescing of the vesicles is probably to be found in the differing temperature and gas content of the lavas. The best-known examples of the coalescing cellular top are the Pewabic lodes. These flows are thin and have ropy surfaces in places. They are so smooth and even that the Quincy mine workings, which follow them, are essentially straight for hundreds of feet. The tops or vesicular portions of the flows are only a few feet thick but very regular, and the banding caused by the larger and the smaller vesicular openings is strikingly even and persistent. (See pl. 58.) All the relations suggest that these flows were very fluid and relatively full of gas when they were poured out. They spread with tops almost as flat and smooth as that of a lake. Possibly flow had ceased before a crust had formed, but if not, the flow of lava under the crust disturbed it very little. In the highly liquid lava, the rising gas bubbles were able to combine into much larger ones that, on reaching the bottom of the crust at any given stage of its formation, coalesced commonly into the extensive flat layers already described. In other parts of these flows, however, the tops are broken into a typical breccia or “fragmental” amygdaloid.

The economic significance of this modification of the smooth-top flow is that the resulting rock is of much higher permeability and therefore much more susceptible to replacement than the normal type, with its small and more evenly distributed vesicles. The broad, flat openings in this coalescing facies are separated by only short distances from other similar openings, so that solutions could move for a long distance parallel to the flow surface without having to penetrate solid rock for more than a small fraction of that distance. It is a striking and significant fact that of the six amygdaloid lodes that have been large producers of copper, only one is of the smooth-top type, and that one, the Pewabic lode or series of lodes, is of this relatively more permeable coalescing variety. Other flows lower in the series show a similar structure but not in so marked a degree as the Pewabic lodes; no ore has yet been found in them.

FRAGMENTAL OR BRECCIATED TOPS

Character.—The rough-top flows, as already indicated, are much less numerous than those of smooth top, but they are of especial interest because four of the six profitable amygdaloid deposits are predominantly of this type and the other two are in part of this type. Most of the other amygdaloid deposits that have yielded considerable copper are also of this type.

The brecciated tops consist of fragments of lava ranging in size from minute grains to massive blocks several feet in dimension. Ordinarily the individual fragments are under 6 or 8 inches in diameter, and the average size is less than half that. In consequence only rarely does one of the larger blocks or slabs project noticeably above the general level of the flow surface. These flows, therefore, though classed in the rough-top type, have a surface less rough and blocky than that of the modern flows to which the name “aa” is commonly applied, and the general smoothness and regularity of the bottom of the overlying flow show that these breccia tops have not been changed from a rough, blocky condition to their present state by crushing and packing due to the weight of rock above.

In shape the fragments range from slabs or irregularly angular pieces through subangular to rounded. In general the larger pieces are the more angular and the smaller ones more rounded, though many small pieces are angular. Large and small fragments are promiscuously jumbled together, though in some flows the smaller fragments predominate near the top and the larger ones near the bottom of the fragmental layer. The general accumulation of material gives an appearance not unlike a conglomerate, and probably for this reason it has sometimes been called “amygdaloidal conglomerate,” though that term as used by Lane apparently does not include these brecciated tops.

There is considerable variation in the texture of different fragments, even of those that are contiguous. A rounded piece entirely surrounded by a fine-grained margin but of coarser center may lie against one that is rather uniformly amygdular and another of fine even grain; or a piece may be fine grained on one side and gradually become coarser toward the other side. Smaller pieces may be uniformly fine or coarse, though even those not more than an inch across may show marked differences in texture.

The greater number of these fragments were vesicular and are now amygdular through filling of the vesicles. Some of the fragments show the same banded arrangement of vesicles as in the smooth tops and undoubtedly were broken from a larger structure of that kind; others may exhibit, particularly near their margins, an arrangement of vesicles more or less parallel to the outlines of the fragment. In many fragments the vesicles near the surface are smaller than those farther in. Very commonly an outer shell a fraction of an inch thick is of dense material containing countless minute, even microscopic vesicles; it closely resembles the thin layer at the very top of the smooth flows and is clearly the result of quick chilling. Some fragments showing this chilled margin around part of their periphery may be coarser grained for the remainder of their circumference, as if broken away from a large mass after the chilled surface had formed and after the interior part had solidified. Still other fragments have a finely granular, almost trappy texture, but fine grain may also be present throughout a fragment in consequence of rapid cooling. Most of the smaller fragments consist of the more finely vesicular material, and most of the larger ones of the more coarsely vesicular, but many exceptions are to be seen. The spaces between the larger fragments are filled with finer material of the same general character grading down to fine particles.

In most of the flows studied that possess the brecciated type of top this mixture of fragmental material gives place downward in the flow rather abruptly to the crystalline trap. The contact between the two is likely to be irregular on a small scale but appears smooth and rather regular when viewed broadly. The trap for a few feet under the fragmental layer may contain included fragments of amygdular rock similar to that in the fragmental zone but generally more rounded, as if partly remelted or resorbed. The layer of trap containing these inclusions is designated the “amygdaloid inclusion zone.” It is present in the traps not only under the brecciated tops but also under some scoriaceous tops or so-called amygdaloidal conglomerates, but it has not been seen under the nonbrecciated smooth tops.

In the tops of the Isle Royale and Osceola flows, which are excellent examples of the brecciated type, there may occur in the midst of the breccia layer slabs of trap a few feet in thickness and as much as 20 feet or even more in length. This material, called by the miners “vein trap,” is likely to contain partly resorbed amygdular patches like those of the amygdaloid inclusion zone. The slabs are commonly parallel to the plane of the lode, but some may be tipped at an angle to it. The fragmental material underneath these slabs is of the same character as that above them. In places these slabs show feeble pipe amygdules on their under side in contact with the lower layer of fragmental stuff. Where this development of vein trap is considerable, the separation of the fragmental material produces a sort of double lode.

A modification of the brecciated top which suggests an approach toward the smooth tops is especially well shown in the Kearsarge lode. In the productive portion of this lode a layer of typical fragmental material ordinarily occupies the upper few feet; the fragments are notably small near the top and coarser below. Without abrupt change the fragments become larger downward, the fragmental character becomes less and less evident, the vesicles increase somewhat in average size, and the banded cellular structure assumes prominence. In short, the chief characteristics of the smooth tops are attained. But this cellular rock underlying fragmental rock is not everywhere continuous over large areas but is composed of blocks or fragments, as if the crust had been broken up while it was still in a semiplastic condition. The blocks may be tilted at an angle with the plane of the lode and show a tendency to chilled margins and coarser interior, suggesting that the final crystallization occurred after the breaking, as indeed is true of the small fragments in the brecciated portion of the lode. In places lava has filled the spaces between the blocks as a cement. Where the brecciated portion of the lode is absent or slightly developed, as outside the productive area of the Kearsarge lode and over considerable tracts within the main productive area, the tendency for the cellular portion to be broken into large blocks is much less conspicuous or is absent. The cellular portion is in places composed of several small flows or gushes showing banded amygdaloid and chill margin.

The intermediate zone of the Kearsarge top has been called “cellular middle lode,” to distinguish it from the “fragmental lode” above. It is not present in all parts of the lode and not equally conspicuous at all places where present. A very little of the same sort of thing is seen here and there in the midst of the Isle Royale lode, which for the most part is of the brecciated type, and it is present in parts of the Baltic lode, especially in areas where the lode is relatively thin.

Still farther down in the Kearsarge top below the “middle lode” horizon the rock becomes coarser in texture, and the vesicles become less numerous and larger and show little tendency to gather in bands. This lower, chloritic zone of the Kearsarge top is called “foot lode.” Material of this character is common on the underside of many of the lodes, such as the Baltic, Isle Royale, Evergreen, and succeeding lodes of that series. Still deeper in the Kearsarge the amygdaloid inclusion zone occurs locally, though it is nowhere conspicuous and in most places is absent, and this passes, as usual, into the main trap of the flow.

The Pewabic series of flows likewise illustrates characteristics of both the cellular and the fragmental tops. The tops of these flows are chiefly of the cellular and cellular coalescing type. In many places, however, the uppermost foot or less of the lode consists of breccia, which gives place downward to the rock with coalescing vesicles. In such places the breccia is commonly made up of fragments of coalescing lode more or less well developed and has obviously resulted from the breaking up of a coalescing top that continued to form beneath it.

In other places over large areas the lode is typically fragmental but of more uniform thickness than is characteristic of “fragmental lode.” Of such character is part of the East lode in the lower levels in the south end of the Quincy mine. Here the lode changes within a few feet from typically coalescing to typically fragmental. The fragmental portion seems to be elliptical in outline and to pitch rather flatly southward; its lower portion extends below the mine workings and has not been traced.

In the upper levels of the Quincy mine the “Main” lode over large areas is typically fragmental, is much thicker than the coalescing portion of the lode, and shows the irregularities in thickness characteristic of fragmental lodes. In the lower levels of the mine this lode is of the coalescing type. The zone of change was not seen, as it lies in a worked out and caved portion of the mine.

The tops of the breccias, though not coarsely jagged, undulate more markedly than the nonfragmental tops. The fragmental material is piled up in hummocks or ridges, separated by basins or valleys. The thicker breccias naturally show greater irregularities of surface than thin fragmental layers like the Kearsarge lode, but alternations of elevations and depressions are generally characteristic of the type. The maximum range from top of hummock to bottom of sag is perhaps 30 feet, and in places the slope from hummock to basin may be steep.

Where this undulating surface of the breccia tops, covered and preserved by succeeding flows and later tilted, is followed by the mine workings, the hummocks bulge up into the overlying flow, whereas in the basins or depressions the overlying trap seems to bulge down into the lode. These irregularities are economically important, not only because they necessitate crooked mine workings but because thick accumulations of breccia are found as a rule to be better mineralized than thin ones near by. It is noteworthy that where the fragmental material has piled up above the general surface of the flow it has also sunk deeper into the underlying trap, and conversely, where depressions occur on the breccia surface, the top of the traps is higher than elsewhere; this produces a podlike thickening and thinning of the breccia layers. Whether or not these variations in thickness of the breccia have any definite relation to the direction of lava flow has not been determined, but a somewhat systematic repetition of variations in certain flows suggests that there may be such a relation.

It is evident that these layers of fragmental material must be much more permeable than the smooth tops, even though these are highly and coarsely vesicular. In part as a consequence of this greater permeability, the brecciated tops, though probably not more than one-tenth as numerous as the smooth tops, include the four great productive lodes—the Kearsarge, Baltic, Osceola, and Isle Royale; moreover the Pewabic only in part represents the smooth tops, there being large areas of fragmental material in this lode.

Origin.—The origin of this fragmental texture in Keweenawan lavas has been variously explained. It has been argued by Hubbard and others that part of the material, at least, is erosion debris. Hubbard and Lane have also explained much of it as a consequence of brecciation due to sliding along the flow contacts at the time of up tilting of the beds, and Hubbard has predicted that the thicker the flow the more brecciation will its top show.

Grant, who studied the flows in Wisconsin, attributed the brecciated tops to flow movement modified in some places by erosion and deposition. The hypothesis that the typical fragmental tops are of sedimentary origin seems to be entirely lacking in support, though many of them have been reworked by erosional and depositional agencies, which have produced the “amygdaloidal conglomerates” or “scoriaceous amygdaloids.”

The hypothesis that they are primarily due to slipping between beds seems also without support. The irregular “dovetailing” of the contact with the overlying flow, due to the hummocky nature of rough tops, did not make such contacts favorable to slipping. Moreover, where the breccia was coarse and open, the top part of it was filled with the lava from the overlying flow, showing clearly that the breccia was present before the overlying flow covered it and of course before tilting of the beds.

The inclusion of amygdaloid fragments partly resorbed in the traps under the amygdaloids seems to indicate clearly that the fragmental tops were formed while the interior portions of the flows were still fluid and presumably still moving. The irregular piling up of the fragments on the flow can probably be best explained by flow forces similar to those in a moving floating ice field.

Such movement would result in much abrasion of the fragments. The fact that where the fragments are piled above the general level they also sink deeper into the flow indicates that they were piled up while the underlying lava was still fluid enough to permit the sinking of the material, as ice sinks deeper where it is piled higher above the water surface.

It seems likely, therefore, that flow movement was a factor in producing the rough tops as we now see them, but it evidently was not the sole factor, because all the flows must have been moving and in general over surfaces of the same type with the same gradient; some solidifying as smooth tops, some as rough. There must, therefore, have been some difference in the lava itself. That the difference was not necessarily very great is indicated by the fact that a top may pass from one type to another within a very short distance. That the composition as we now find it was not the cause is indicated by the close similarity in composition of flows with tops of different types and the presence of tops of different types on parts of the same flow.

The influence of the gaseous constituents of lavas that escape during solidification is a factor not easily studied in these old flows, but it has been given much study in recent and active flows. Washington[30] has recently summarized the evidence and the views of various writers on this subject, as well as contributing the conclusions from his own study, and as his summary has so direct a bearing on the formation of the tops of different types in this district, it is in large part quoted below.

> The cause of the differences between the two forms has been the subject of much discussion and is still an unsolved problem, the chief difficulties centering about the formation of aa or block lava. * * *
>
> According to Button “pahoehoe is formed by small offshoots of very hot and highly liquid lava from the main stream driven out laterally or in advance of it in a succession of small belches. These spread out very thin and are quickly cooled.” On the other hand, “the fields of ‘aa’ are formed by the flowing of large masses of lava while in a condition approaching that of solidification.” * * * Dutton lays stress on the much greater thickness of the “aa” flows and regards this and the consequent differences in cooling as the causes of the diverse characters.
>
> Dana thinks that “in an ‘aa’ flow the lava must have been subjected to some deeply acting cooling agency,” and that “the cooling was not from above downward, as in pahoehoe, but largely from below upward.” He concludes that this cooling agency is subterranean water in the region passed over an explanation which is combated by Hitchcock and which does not seem to be supported by field evidence.
>
> Daly attributes the difference to “gas control,” which he thinks is shown by the different vesiculation of the two forms. The vesicles in pahoehoe are relatively more numerous, more regular in form, being mostly spherical, smaller in size, and more evenly distributed than in “aa,” in which they are irregularly scattered through the mass, most of them of very much greater size, relatively fewer, and of irregular shape, many being much elongated. Their total volume is generally less per unit volume of rock than in pahoehoe, and “the ‘aa’ vesicle has undoubtedly grown through the coalescence of many bubbles of gas. * * * The difference in field habit is thus explained by the relative abundance of volatile matter and, still more, by the evenness of its distribution.”
>
> Day and Shepherd[31] call attention to “the rapid expansion of the gases with the release of pressure (as ‘aa’ lava reaches the surface), which is a cooling phenomenon, and which, if the expansion takes place suddenly from a high pressure into the air, might be extremely rapid. * * * Such rapid expansion and consequent cooling, when occurring suddenly at the surface, may very well be the sufficient cause of the ‘aa’ lava formation. Great blocks appear to have cooled in this way so rapidly that no opportunity was given for the suddenly projected and rapidly expanding lava to ‘heal’ and resume liquid flow. The projected masses are cooled almost instantly throughout their mass and remain discrete blocks.” Doctor Day’s belief is that pahoehoe lava is the high-temperature form, containing relatively little gas, whereas the “aa” issues at a lower temperature, contains much gas, and cools quickly throughout its mass because of the rapid expansion and elimination of the gas.
>
> Jaggar thinks it “probable that the quantity of confined gas, in solution or in bubble form, controls the method of freezing. Possibly the gases are nearer equilibrium in pahoehoe than in ‘aa.’ The heat equation plays an important role, and this involves reaction between the gases as well as their oxidation in air. Gas expansion may be more rapid in ‘aa’ and so induce internal solidification. Furthermore, there are enormous differences in the state of oxidation of the iron at the moment of internal solidification, and as yet we know nothing of the progress of crystallization in the field.”
>
> At Vesuvius, according to Mercalli,[32] the most rapid flows and those which contain most gas take the “aa” form, whereas the slower and more viscous lavas generally are of the pahoehoe type. He thinks that the difference between the two depends on “different conditions of cooling,” but that difference in the angle of slope has a marked effect. Similar views are expressed by Von Waltershausen[33] in describing the lavas of Etna. * * *
>
> There seems to be general agreement in the belief that the “aa” form is produced from a highly gas-charged lava by rapid cooling due to the escape of gas, but the question as a whole must still be considered unsettled. There are, however, two or three differential features of the two forms of lava which do not seem to have as yet been studied in connection with this problem but which may throw some light on it. These are the relative amounts of the iron oxides, the different degrees of crystallinity of the two forms, and the different sizes of the respective flows.

After showing that there is no essential difference in chemical composition but that the smooth tops are distinctly less crystalline than the rough, Washington continues:

> Inasmuch as the chemical compositions of the “aa” and the pahoehoe forms of these lavas are identical some other factor or factors, physical or physico-chemical, must be sought to explain these differences in the crystallinity, which appear to be connected with the structural and field differences of the lavas.
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> Any difference in the initial temperature at the time of extrusion does not seem to be adequate in itself, as this difference would

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[30] Washington, U. S., The formation of aa and pahoehoe: Am. Jour. Sci., 5th ser., vol. 6, pp. 409-123, 1923.

not be very great and would be eliminated soon after extrusion.

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The only factor that appears to be competent to serve as an adequate cause is the "gas content of the magma. * * * That the magma which solidifies as "aa" has a very high gas content is commonly recognized. It is shown by the loud roaring and hissing noises of a moving "aa" flow, the numerous flames on the front and over the surface of "aa" flows, and by the abundance of noxious gases, which often make near approach difficult. The lesser gas content of pahoehoe is evident from the much quieter, almost noiseless flow and the absence of flames. Indeed, so quiet and so free from gas are most pahoehoe flows that one can easily (apart from the heat) study them from their brinks. Although pahoehoe flows are fairly fluent on their extrusion their viscosity increases very rapidly. An excellent illustration of this is given by Brigham[34] in his description of a pahoehoe flow issuing from a dome. "It was white-hot cream when it came out from under the crust, hut in the distance of perhaps a foot had changed to a cherry red molasses, while a few feet more transformed the stream into full-red tar."

The formation of the two forms of lava takes place about as follows, according to my conception of it. Pahoehoe lava comes out highly heated, probably in large part by internal gas reactions, but not highly charged with gas, much of this having been lost by simmering in the throat near the surface or elsewhere in the course of flow. Because of the high temperature the greater part of the comparatively small amount of gas that remains after effusion is soon lost, whereby the fluidity of the lava rapidly diminishes and with it the possibility of internal molecular motion, so that an early stop is put to crystallization, although the semimolten, highly viscous glass is still capable of slow continuous motion. As the temperature falls and the viscosity increases, the comparatively small amount of gas still present in the magma is gradually expelled from solution and there being few solid points to serve as nuclei and the material being very viscous, the gas is liberated quite uniformly throughout the mass and forms small, spheroidal, rather uniformly distributed bubbles. Slabs of pahoehoe generally show an increase in size and number of vesicles toward the bottom, an effect probably caused by the quicker cooling and solidification of the upper part, which radiates its heat into the air. * * *

"Aa" issues at a lower temperature than pahoehoe, certainly more highly charged with volatile matter, so that the gas present renders the "aa" magma, in spite of its lower temperature, initially much more fluid than is the pahoehoe. Under these conditions of great fluidity and lower temperature the crystallization of labradorite and augite begins early and proceeds with rapidity. The fluidity of the liquid portion and the consequent rapidity of crystallization are maintained and, indeed, enhanced by several circumstances. In the first place, the separation of the crystals, in which the gases are not appreciably soluble, increases the gas concentration (and the pressure) within the remaining liquid, thus maintaining a high degree of fluidity and consequent possibility of internal molecular movement, so that crystallization is facilitated. This increase in gas concentration rapidly reaches or exceeds the point of saturation, the liberation or desolution (if I may be permitted to coin a word) of the gas being greatly facilitated by the presence of innumerable crystals whose angles and edges serve as nuclei and give abundant opportunity for the escape of gas, in virtue of the action of such solid points as centers of the liberation of gas. The gas will thus tend to coalesce into large bubbles and so pass out of the liquid, which remains constantly saturated with gas throughout the continuous crystallization and hence remains very fluid and favorable to crystallization.

Two other factors also tend to preserve the fluidity of the gradually diminishing liquid portion of the lava. * * * The one is connected with what has been called the "second boiling point"[35]—that is, the increased gas pressure resulting from the formation of crystals in a cooling liquid. The formation of crystals in a liquid lava gives out latent heat,[36] as silicate minerals appear to be normal in this respect, so that the crystallization itself will tend to maintain the temperature of the still molten portion or diminish the slope of the cooling gradient. It follows that, in so far as we now know the thermal behavior of silicates, the crystallization or partial solidification of the lava may have a very appreciable effect in maintaining the fluidity of the remaining liquid portion by retarding the increase in viscosity.

The other possible factor is indicated by study of the thin sections of the crystalline basaltic lavas of Hawaii and of other localities. This shows that feldspar begins to crystallize first, augite and magnetite belonging to the later stages of crystallization. * * * Because of this early crystallization of feldspars the portion of the lava that remains liquid becomes increasingly femic and therefore more and more fluid, so that the flow of the lava stream is maintained, in spite of the abundant crystallization, and with its continued liquidity also the facility for crystallization.

The liberation of gas from the mass of "aa" will thus be increasingly rapid, possibly violent toward the end, and the crystallization of the lava which forms "aa" is consequently very rapid after a certain degree of fluidity has been reached, the great fluidity of the steadily diminishing liquid portion of the flow being maintained up to the point of complete solidification, as is demanded by the microtextural features of the "aa" lava. This accounts well for the fantastic, rough surface forms and for the large, elongated, random bubbles, both of which are characteristic of the "aa" form.

The conclusions reached by Washington from the study of recent and active flows strongly suggest that varying gas content was a controlling factor in forming the different types of tops in the Keweenawan lavas.

"SCORIACEOUS TOPS"

The misnamed type of rock known locally as "scoriaceous tops" has already been described in the section on amygdaloidal conglomerate (p. 20). Briefly, it consists of amygdaloidal fragments in a matrix of fine basic sand which grades downward into normal amygdaloidal rock and in many places upward into fine basic sediment and at numerous horizons finally into felsitic sandstone or conglomerate. As the name implies, lodes of this type have been regarded as the result of explosive volcanic action, the sediment being considered volcanic ash. The Ashbed is the type example.

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[31] Geol. Soc. America Bull., vol. 24, p. 598, 1913.

[32] Mercalli, G., Vulcani attivi della terra, p. 179, 1907.

[33] Von Waltershausen, S., Der Etna, vol. 2, pp. 393 et seq., 1880.

[34] Brigham, W. T., The volcanoes of Kilauea and Mauna Loa: Bishop Museum Mem., vol. 2, No. 4, p. 141, 1909

The “scoriaceous amygdaloids” are more permeable than the smooth cellular tops but less permeable than the brecciated tops, because the interstices between the fragments are filled with a fine sandy to clayey sediment.

Of the numerous examples of this type the Ashbed lode, on which the Atlantic, Copper Falls, and other mines are located, is the only one from which ore has been produced.

ALTERATION

ALTERATION OF TRAPS

Except for the alteration effected by the copper-depositing solutions, the basaltic rocks are surprisingly fresh in view of their basic composition and their great age. As the ore-depositing solutions moved in quantity only along the more permeable pathways, the dense traps have escaped most of the chemical and mineralogical changes that accompanied the deposition of copper. Glaciation largely removed whatever weathering products had been formed earlier, and since glaciation only incipient kaolinization and limonitization and slight physical decomposition of the traps have occurred, even where the rocks were not covered by glacial deposits.

The principal alterations, aside from ore deposition and surface weathering, occurred in the olivine and the magnetite; the pyroxene and the feldspar of the traps are usually unaffected. The olivine, which at the time of crystallization was common in many of the traps, is now preserved in relatively few. Its former space is filled with serpentine and hematite that have replaced it. This breakdown appears to have caused no marked change in chemical composition within the limits of the olivine individuals but to have been, rather, a rearrangement of the elements into minerals of greater stability under the conditions existing.

The magnetite was altered more or less completely to hematite. The hematite seems to have worked in from the surface, but it also permeated all through the magnetite individuals, which therefore present a pitted appearance under the microscope. In places where magnetite is completely altered to hematite minute irregular stringers and tendrils of hematite extend out from the magnetite grain among the surrounding minerals, suggesting that in the alteration of the iron mineral an increase in volume forced some of the hematite to lodge outside the original boundary of the magnetite. Some of the magnetite was evidently titaniferous, for its alteration has produced numerous granular particles of a nonmetallic mineral, probably titanite, in the midst of the more abundant hematite. The alteration of these two minerals, so far as has been ascertained, was almost magmatic—-that is, it took place very shortly after the rock had solidified, unless, indeed, these early iron-bearing minerals were already altered by the time the pyroxene and the feldspar had crystallized around them, as is discussed later (p. 53). The dominant tendency in the alteration of both these minerals was the conversion of ferrous to ferric iron. This oxidation of iron suggests association in origin with the hematite in the tops of many of the flows and is again referred to in that connection (p. 35).

ALTERATION OF THE LAVA TOPS

Alteration of the tops of the lava flows is of two types, produced at different times and by different causes—the development of plentiful hematite and the filling of the vesicular and other openings, together with more or less replacement of the rock by lode minerals.

The formation of hematite caused or accompanied in some of the tops an increase in iron content, notably above that in the deeper parts of the flow. Whether this increase is an alteration or an original magmatic effect is not altogether clear; the question is discussed on page 36.

The cavities or vesicles of the lava tops, in the main, long remained empty, though probably some chlorite and perhaps feldspar was deposited in them during the cooling of the lava. There seems no reason to believe that the vesicles of one flow were filled before the next flow appeared, nor that during the general period of lava extrusion there were successive periods of vesicle filling. The vesicles appear to have been filled after all the flows had been spread, the overlying thick sedimentary formation deposited, and the rocks tilted to their present attitude. Practically all the fractures, large and small, that were produced by deformation of the rocks carry the same minerals as those which form the amygdules. The minerals of the amygdules and of the fractures are, in fact, identical with the gangue minerals accompanying the copper. They are therefore further discussed under the heading “Ore deposits” (p. 107).

RED COLOR OF AMYGDALOID TOPS

STATEMENT OF THE PROBLEM

The oxidation and concentration of the iron in the tops of the flows appear to have received little investigation; these processes, therefore, will be discussed in considerable detail, and several possible methods by which they might have been effected will be considered. The conclusion reached may be stated at the outset; it is that both, the oxidation and the concentration of iron were accomplished by gases escaping from the solidifying and crystallizing lava. The inclosed gases were either neutral or reducing toward iron at the temperature at which the lava emerged but became strongly oxidizing as the temperature decreased, with the result that much of the ferrous iron was converted to the ferric state, the conversion being more and more complete as the upper part of the flow was approached.

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[35] Morey, G. W., The development of pressure in magmas as a result of crystallization: Washington Acad. Sci. Jour., vol. 12, p. 219, 1922.

[36] Mercalli (Vulcani attivi della terra, p. 189, 1907) attributes the long-continued preservation of heat by lava flows, often amounting to several years, to this development of latent heat of crystallization. In July, 1914, Doctor Day and I could scorch paper in crevices of the flow of 1910 at Etna.

A striking feature of the tops of many of the Michigan flows is their red color, which ranges in intensity from bright brick-red through darker and duller shades to faint browns but always contrasts with the dark gray or greenish gray of the deeper portions of the flow. This red hue may disappear before the bottom of the amygdular zone is reached or it may extend for a short distance into the trap. It is useful in the recognition of amygdaloid beds on outcrops, in crosscuts, or in drill cores. It is present in many of the cellular smooth-topped amygdaloids and is strongly developed in the brecciated tops. In the "scoriaceous tops" or amygdaloid conglomerates the red color may be rather faint or altogether wanting, although the fine mud is usually brown. This red color, which is due to the presence of ferric oxide, is present in all the amygdaloid lodes (and in the felsite conglomerates as well) from which noteworthy quantities of copper have been produced, and some explanation of it is involved with almost every theory of the origin of the copper deposits that has been advanced. It therefore merits careful investigation.

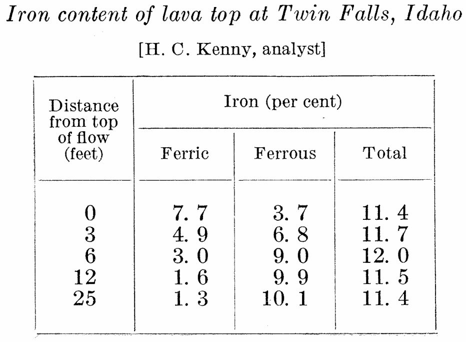
The enrichment of the lava tops in ferric oxide has been ascribed by some observers to weathering, a process which was supposed to be facilitated by the brecciation that certain tops have undergone. Other investigators, laying stress on the fact that all the red tops are mineralized in one way or another, have inferred that ferric oxide was a by-product of various kinds of mineralization. The present discussion may well begin by putting these hypotheses to the test.

The problem is presented in simplified form by the red tops which have been described as occurring in many parts of the world on lavas that have been erupted in comparatively recent times and appear to be virtually unaltered. Such lavas were studied by T. M. Broderick in the Snake River and Columbia River regions for the purpose of obtaining light on the history of the Michigan flows.

RED TOPS OF UNALTERED WESTERN FLOWS

The red color is well shown in the tops of many basaltic flows of the Snake River and Columbia River lava plains. In both regions the cellular, non-fragmental tops prevail. The Snake River flows, with their vesicles still unfilled, have not been attacked by later mineralizing solutions, such as have caused the marked alteration of the Keweenawan flows, and they have escaped almost wholly the limonitic alteration and the disintegration which the surfaces of the older Columbia River flows have suffered in consequence of weathering. The Snake River flows are therefore well suited to show simply and directly the chemical and mineralogical changes of which the reddening is the visible effect.

A series of specimens taken at different intervalsI from the top of a flow 40 feet thick at Twin Falls, Idaho (fig. 2), show the following contents of ferrous and ferric iron:



Iron content of lava top at Twin Falls, Idaho

[H. C. Kenny, analyst]

Distance from top of flow (feet)	Iron (per cent)		
	Ferric	Ferrous	Total
0	7. 7	3. 7	11. 4
3	4. 9	6. 8	11. 7
6	3. 0	9. 0	12. 0
12	1. 6	9. 9	11. 5
25	1. 3	10. 1	11. 4

These results show a virtually constant iron content from the surface down, but a marked and progressive change in the state of oxidation of the iron. At the surface 70 per cent of the iron is ferric; this percentage gradually diminishes, so that in the lowest sample, from about the middle of the flow, less than 12 per cent of the iron is ferric.

Examination of polished and thin sections of the minerals in these flows shows that the chief iron-bearing minerals in the deep parts of the flow are magnetite, olivine, and pyroxene. In the upper, red portion, hematite accounts for most of the iron. Some of the hematite was formed by alteration from magnetite or, together with serpentine, from olivine; but some shows no sign of ever having been anything else, and this occurs in platy or bladed crystals, generally of minute size, found characteristically in the glassy matrix surrounding the plagioclase crystals. The plagioclase is practically unaltered.

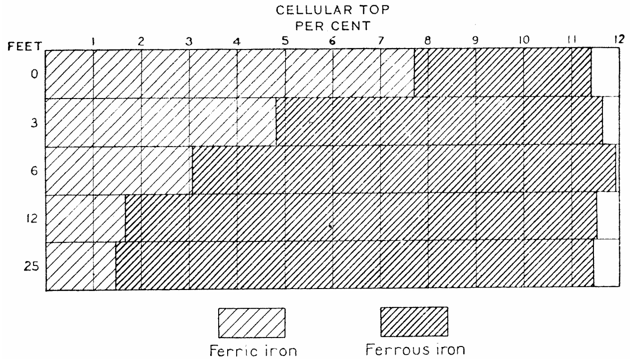
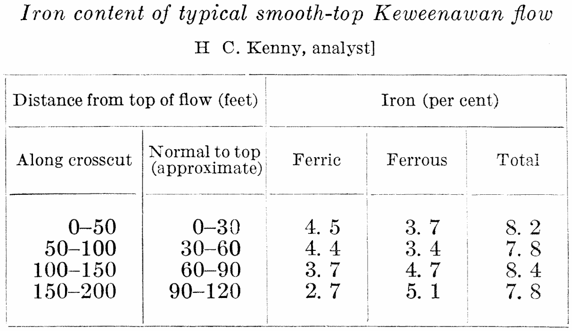


FIGURE 2.—Change in iron in lava top at Twin Falls, Idaho

Nothing in the chemical results or in the minerals present in these Idaho flows suggests that iron has been added to the tops. No vesicle fillings or veins of later minerals are to be seen. A partial rearrangement of the iron and an increase in the degree of its oxidation near the tops of the flows seem to be all that has happened. These changes can not be ascribed to any later alteration but appear to have been accomplished by the time the lava had solidified or very shortly afterward.

OXIDATION IN SMOOTH-TOP FLOWS OF KEWEENAWAN SERIES

Many of the Keweenawan flows show the same kind of transition from unoxidized trap to oxidized top as the more recent western lavas. The following analyses of samples from a smooth-top flow, the second flow below the Wolverine sandstone at the Wolverine mine (fig. 3), indicate that the changes involved are closely similar to those represented in the analyses of the Idaho flow. The samples are grouped into composites each of which represents a horizontal distance of 50 feet in a crosscut which traverses the flow at right angles to the strike from top to bottom. The dip of the flow is approximately 40°.



Iron content of typical smooth-top Keweenawan flow

H C. Kenny, analyst]

Distance from top of flow (feet)		Iron (per cent)		
Along crosscut	Normal to top (approximate)	Ferric	Ferrous	Total
0–50	0–30	4. 5	3. 7	8. 2
50–100	30–60	4. 4	3. 4	7. 8
100–150	60–90	3. 7	4. 7	8. 4
150–200	90–120	2. 7	5. 1	7. 8

Here, as in the Snake River lavas, the total iron is essentially constant, but the ferric iron increases steadily toward the top and the ferrous iron decreases almost as steadily. Both the Idaho and the Michigan analyses show that the red tops are the extreme expression of a change which has taken place throughout the flow. Two causes have produced the reddening—namely, the greater abundance of hematite and the decreasing size of its particles toward the top of the flow. The effect of fineness of division of a small amount of hematite in giving a brilliant red color to agates and jaspers is well known, and a similar effect is clearly revealed by microscopic study of these Michigan lavas.

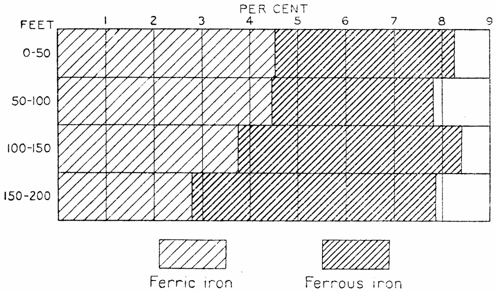
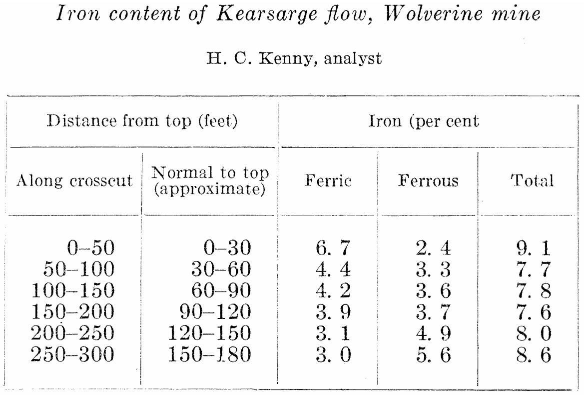


FIGURE 3.—Iron content of smooth-top flow (second flow below Wolverine sandstone, Wolverine mine)

OXIDATION AND CONCENTRATION IN BRECCIATED-TOP FLOWS

Although the red flow tops of the cellular, smooth-top type contain so far as determined about the same proportion of total iron as the body of the flow some of the fragmental tops contain a considerably higher percentage of total iron than the rest of the flow, but, just as in the nonfragmental tops, most of the iron is in the ferric state and occurs as hematite. (See pls. 62, 63.) The Kearsarge lode is a conspicuous example of concentration of iron in the top and is the one that has been most studied. The following table shows the iron content at varying distances from the top of the Kearsarge flow in a single section. Distances are horizontal; the dip of the beds is 35° to 40°.



Iron content of Kearsarge flow, Wolverine mine

H. C. Kenny, analyst

Distance from top (feet)		Iron (per cent		
Along crosscut	Normal to top (approximate)	Ferric	Ferrous	Total
0–50	0–30	6. 7	2. 4	9. 1
50–100	30–60	4. 4	3. 3	7. 7
100–150	60–90	4. 2	3. 6	7. 8
150–200	90–120	3. 9	3. 7	7. 6
200–250	120–150	3. 1	4. 9	8. 0
250–300	150–180	3. 0	5. 6	8. 6

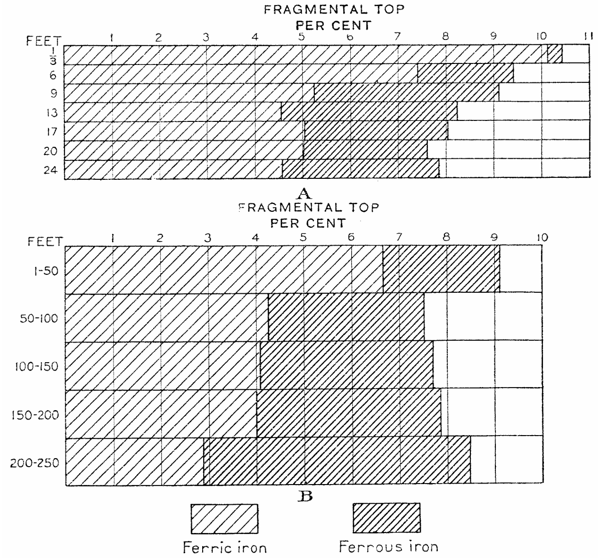
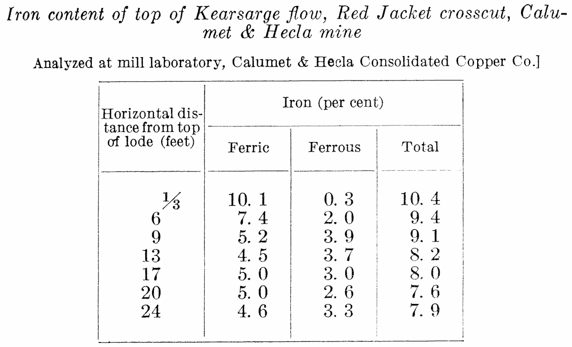


FIGURE 4.—Iron content of Kearsarge flow. A, Calumet & Hecla mine 81st level; B, Wolverine mine

This series of specimens, which represents a section of the entire flow from top to bottom, shows a concentration of iron in both top and bottom as compared with the middle portion, the greater concentration being at the top. (See fig. 4, B.) The ferric iron content increases steadily and the ferrous iron decreases steadily from the bottom upward. The upper part of the Kearsarge flow has been sampled at shorter intervals to show still more closely where the notable changes in proportion of ferrous to ferric iron and the most marked increase of ferric iron are to be found (fig. 4, A), and the results are as follows:

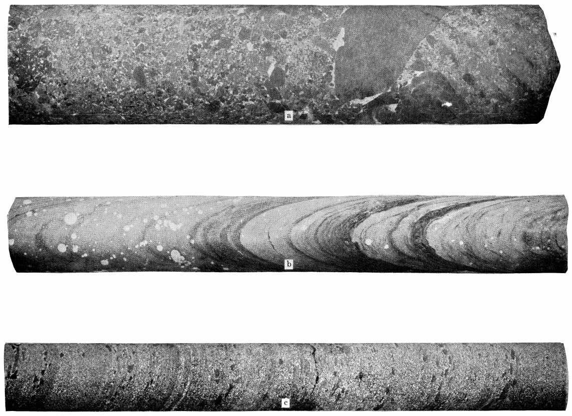


Iron content of top of Kearsarge flow, Red Jacket crosscut, Calumet & Hecla mine

Analyzed at mill laboratory, Calumet & Hecla Consolidated Copper Co.]

Horizontal distance from top of lode (feet)	Iron (per cent)		
	Ferric	Ferrous	Total
⅓	10. 1	0. 3	10. 4
6	7. 4	2. 0	9. 4
9	5. 2	3. 9	9. 1
13	4. 5	3. 7	8. 2
17	5. 0	3. 0	8. 0
20	5. 0	2. 6	7. 6
24	4. 6	3. 3	7. 9

U. S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 144 PLATE 55

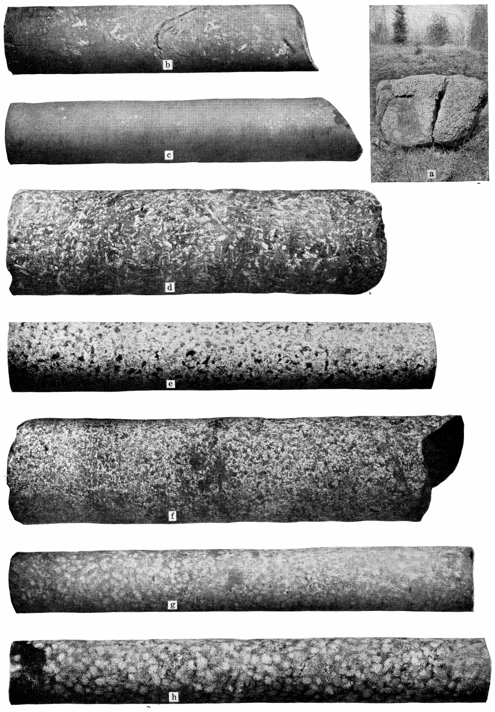


TEXTURE OF SEDIMENTARY ROCKS AS SHOWN IN DIAMOND-DRILL CORES

a, Felsite conglomerate (Keweenawan); b, Jacobsville (" Eastern ") sandstone, showing bleached areas; c, Jacobsville (" Eastern ") sandstone, showing "mud flakes"

[Plate 55. Texture of sedimentary rocks as show in diamond-drill cores.]

U. S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 144 PLATE 56

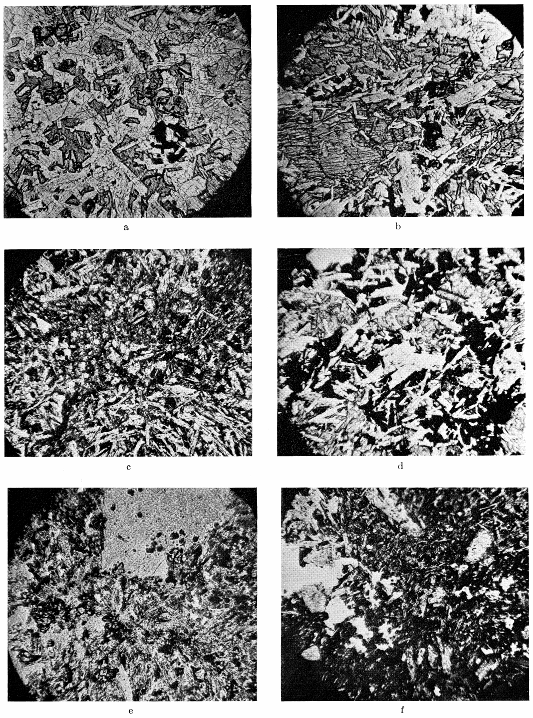


TEXTURE OF LAVAS AS SHOWN IN DIAMOND-DRILL CORES

a, Ophitic texture as seen on weathered surface; b, porphyrite; c, melaphyre; d, "dolerite," pegmatitic facies of traps; e, finer glomeroporphyrite; f, coarse glomeroporphyrite; g, banded ophite; h, typical ophite

[Plate 56. Texture of lavas as shown in diamond-drill cores.]

U. S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 144 PLATE 57

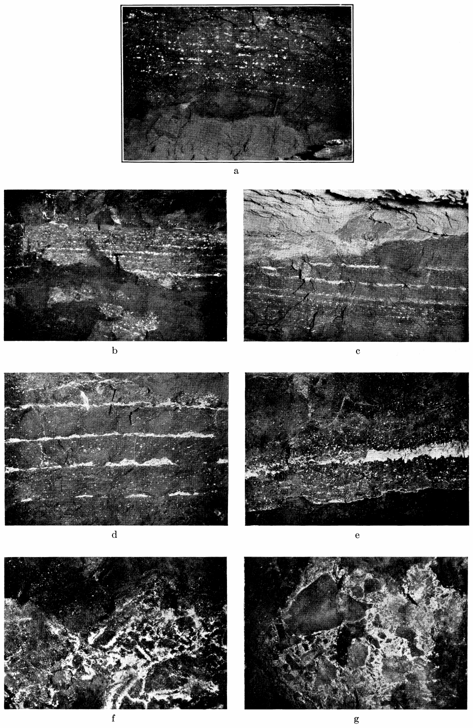


TEXTURE OF LAVAS AS SHOWN IN MICROSCOPIC SECTIONS

a, Typical ophite from the Greenstone; b, diabasic structure in flow below the Calumet Hecla conglomerate; c, trap just above the Calumet Hecla conglomerate; d, fairly fresh ophite from Osceola flow; e, foot trap from Kearsarge flow; f, typical "foot lode" from Kearsarge flow. All × about 30

[Plate 57. Texture of lavas as shown in microscopic sections.]

U. S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 144 PLATE 58



TEXTURE OF FLOW TOPS AS SEEN IN LODES

a, Cellular lode, tending toward coalescing; b, cellular lode, somewhat coalescing; c, coalescing lode; d, banded coalescing lode; e, strong band in coalescing lode; f, g, fragmental lode. All from Quincy mine

[Plate 58. Texture of flow tops as seen in lodes.]