TABLE XIX.

Keweenawan sedimentaries and the Lake Superior sandstone.

	1	2	3	4	5	6	7
SiO_2	55.09	63.09	69.78	75.19	87.02	82.60	77.18
Al_2O_3	15.41	18.58	15.43	10.78	7.17	8.32	9.69
Fe_2O_3	9.04	2.17	7.93	4.01	3.91	0.28	3.20
FeO		2.73		1.05	...	...	...
MgO	2.49	2.67	1.17	0.95	.06	0.18	1.48
CaO	7.02	1.11	.49	2.36	.11	0.55	0.26
Na_2O	4.01 diff	4.54	2.42	1.93	.22	...	0.18
K_2O	...	.54	2.64	0.93	1.43	6.49	4.67
H_2O-	5.03 loss	2.69	2.61	...	tr.	0.99	2.90
H_2O+	inc. CO_3			...			
TiO_2	...	.99	...	...	...	...	...
P_2O_5	Cl. .18	.12	...	...	...	0.05	0.21
CO_2	...	...	...	...	...	...	...
S	.04	tr.	...	...	...	...	...
Cu	1.70	.008	...	...	...	$SO_3$0.31	0.23
Pd	...	tr. +	...	...	...	...	...
MnO_2	...	.22	...	...	...	0.13	...
Sp. Gr.	...	...	100.36 2.43!?	...	99.92 2.18	...	...

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

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

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

CHAPTER III.

MICROSCOPIC PETROGRAPHY.

§ 1. HISTORICAL INTRODUCTION.

The mineralogical microscopic petrography of the fresh unaltered Keweenawan rocks is not very complicated. Here again as in the chemical work the most thorough and excellent recent work has been done by Alexander N. Winchell.[1] But notes will be found in the annual reports by F. E. Wright, Gordon and myself. The older work of Wadsworth, Irving[2] and Pumpelly[3] was excellent for its time and a number of other papers are cited by those authors, and need not be repeated here.[4] Suffice it to say that almost all the work on this subject is found either in the United States, Wisconsin, Minnesota or Canadian Survey reports and that all these Surveys have done work upon Michigan rocks as well as upon the rocks of their own region since the development of the copper industry has been much greater in Michigan, thus affording better chance to study the rocks. My own work on the petrography is largely incorporated in Vol. VI of these reports and since then I have done comparatively little microscopic work that brought out new mineralogical facts. Perhaps the most interesting is the recognition of a peculiar aegrite or acmite in a Keweenawan dike rock cutting the Virginia slates.[5] I would call attention to the early use in Volume VI of Becke and Exner's method of determining differences of refraction (p. 154). One may grasp a popular idea of this method and its later improvements if one will hold a bottleful of water close to a window at one side. Then one will see that the light coming in from the window suffers total reflection on the further side of the bottle from the window. Thus any object obliquely illuminated lying in a medium of less re-

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

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

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

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

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

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

[5]Report for 1908, p. 304.

fraction (if the border between the two media is anything like the bottle) will have a similar effect,—a bright border on the side opposite to that from which the source of light is. It must be remembered that the field of view is reversed in the microscope so that the effect is apparently reversed. If the index of refraction of a grain immersed in a fluid is clery close to that of the fluid, it may very easily be seen that for certain wave lengths the index of refraction will be greater than that of the fluid, for others less. Then those rays for which the index is greater will have, just like the bottle, a bright border on the side furthest from the source of

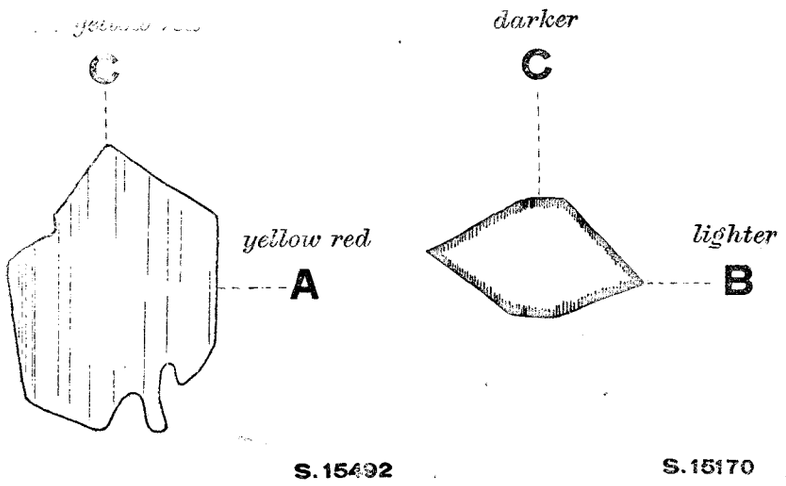


Fig. 16. Illustrates optical properties of altered olivine. Reproduced from Vol. VI, Part 1, Figure 23.

light which will, however, be distinctly colored. If, instead of being a bottle, it is a bubble which is surrounded by a fluid of higher index the bright spot will be on the side nearest to the source of light, as may also be easily seen by shaking up the fluid in the bottle and watching the effect on the bubbles, and if the fluid is so near the index of refraction of the immersed grain for some wave lengths above and others below we shall have the bright border on the far side for one color and on the near side for another. Practically the grains will be bluish on one side and yellowish on the other. This method has been worked up very elaborately lately by Schroeder Van der Kolk and F. E. Wright of Washington and a series of fluids with different indices put up so that by a little study one can tell whether a grain is above or below in

index that of the various fluids and thus determine its character. Not only that, but if, as is generally true, the polarizer of the petrographic microscope allows the light to go through only in one direction,—by revolving the grain we get the index for different directions much more closely than heretofore.

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

§ 2. MINERALS.

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

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

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

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

There is very often a tendency toward idiomorphism even in the ophitic texture. This is sometimes entirely imperceptible in thin sections but on studying the flashes from a specimen showing the luster mottling it will often appear that they are elongate parallel to the vertical axis, or bounded by straight lines which have a definite crystallographic meaning. A slight tinge of violet such as is given by titanium is especially common in ophitic augite. The more markedly titaniferous kinds are rare. Decomposition of augite to chlorite is very abundant but I do not think that all the chlorite replaces augite. Some of it seems to occupy original interstices left vacant or filled only with hot water in the crystallization and shrinking of the augite. Epidote also replaces the augite. Hornblende seems to replace augite only in a very few cases and then mostly when an augitic rock has been metamorphosed by injection with some later intrusive. There is a zone of hornblende developed from the augite around the Mt. Bohemia gabbro as described by Wright on page 375 of the annual report for 1908. (See also Vol. VI, p. 73.)

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

Quartz and other forms of silica. Very recently quartz has assumed a much greater interest owing to the fact that it has been found that silica crystallizes in three different forms according to the temperature and these limits are pretty carefully determined. I regret that most of the work was done before the methods determined by Mügge and Wright and Larsen were developed so that I am not able to speak as definitely as I should like about this matter. Tridymite has never been found, but in such old rocks it probably would in any case have been changed to forms more stable at low temperatures by this time.

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

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

There is, however, little question from the form of the quartz in the quartz porphyries that much of that crystallized between 550 degrees and 800 degrees C. The vein quartz like that described by Lincio[9] was formed at lower temperatures.

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

Something that may be taken for magnetite is widely distributed as a fine dust, but it is by no means certain whether it is or not. In one dike north of Bessemer there seems to be both graphite and magnetite present under conditions which make it extremely hard to tell just how much is magnetite and how much graphite in thin sections. I think the graphite is more feathery. In alteration spots and around amygdule cavities it gathers into club-shaped and branching aggregates and sometimes iron oxide outlines brecciated and fragmental and perlitic textures. Distinct crystalline and red hematite is more rare. Ilmenits or titaniferous iron ore occurs and occasionally its white alteration product known as leucoxene. This seems to occur also in some of the epidotic replacements. Ferritic discoloration gives to the sedimentary beds and to the red amygdaloids their characteristic color.

Green decomposition products or viridite. There is an old name, —viridite,— which is a convenient one for the secondary hydrous magnesian silicates of green color, which probably form an isomorphic series. Their optical properties have been fairly fully discussed in Volume VI, Part I, and also by Winchell in his recent text-book on optical mineralogy. It is probable that ferrous iron is a very important constituent of the group. I can readily distinguish the three following varieties:—(1) Serpentine with its usual properties after olivine, (2) delessite or iron chlorite, probably including such varieties as strigovite, etc. This is more bi-

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

refringent and more fibrous than (3) the ordinary chlorite. Chlorastrolite, as Hawes says, seems to be a compound product of some alteration which is changing to chlorite the hard amygdules of some other substance, often prehnite. Chlorastrolite has been found recently not only in Isle Royale on the patch indicated in my map of Isle Royale, Pl. I, where it was originally found but in a number of beds on Keweenaw Point. For instance, a good deal was developed in the workings of the Keweenawan Copper Company at the Medora shaft, and it has been recognized by Dr. Hubbard at a number of places on Keweenaw Point. It there occurs in an amygdaloid which is reddened and decomposed, in which the decomposition has gone on faster in the body of the rather coarse amygdaloid than in the amygdules. Under such conditions a change takes place around the borders of the prehnitic amygdules. In view of what we know of the concentric character of amygdule filling, however, it is not always easy to prove that the green chatoyant effect of chlorastrolite is not due to an original rind of chlorite. Again, the centers of the amygdules are sometimes occupied by quartz and I should not wish to say that thomsonite or some other zeolites may not sometimes be the original mineral rather than prehnite. A. N. Winchell* (p. 410) seems to be inclined to think that some "chlorastrolite" of northern Minnesota should be grouped under thomsonite. In any case the chemical reaction seems very much that which we have found to be characteristic of decomposition, for instance, of the Calumet and Hecla boulders where magnesia and iron replaces lime and perhaps soda.

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

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

Wollastonite? In the Amherst mineral collection there is a piece of considerable size labelled "table spar, Isle Royale" in Jackson's own handwriting as Professor Emerson informs me, and of this he was kind enough to give me a small piece. I think there

*Optical Mineralogy, p. 410.

can be no doubt that this is the same mineral as that referred to in his report on page 491 or at least the Isle Royale variety of it.

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

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

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

My Dear Prof. Lane:

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

Most sincerely yours,

WM. E. FORD.

Calcite is abundant in large crystals and amygdules, in replacement and in veins. Bands of pressure twinning are not uncommon

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

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

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

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

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

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

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

with very similar substances, except that in his figure and in mine different pinacoids seem to have been present.

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

Apatite seems to be a mineral which crystallized early in sharp needles, or possibly slowly throughout the process of crystallization but has a strong tendency to segregation. Possibly the little needles simply floated in the residual magmas. It also seems to occur abundantly in the interstices in the last crystallizations from the mother liquor in needles shooting across the cavities. It suggests the presence of chlorine in these waters (See Sp. 17530, a doleritic melaphyre, 75 paces N., 1050 W. of the S. E. ¼ of section 33, T. 57 N., R. 32 W., below the Kearsarge amygdaloid in the Allouez gap).

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

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

§ 3. TEXTURES.

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

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

This is to me a reasonable explanation, not only of this fine grained marginal form of gabbro, but of some of the felsite ground masses, and it is a question whether a rock of this sort should be classed as originally crystalline or a devitrified rock. The irregular distribution of minerals or gases which tend to promote crystallization through the magma and their irregular escape also produce differences in crystalline texture, even after the rock for many purposes may be considered as solid,—for instance, capable of fracture. Whether indeed we may ever speak of a glass as absolutely

free from viscosity is a question over which physicists would disagree although there is no doubt that in many cases the viscoscity is practically infinite.

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

(a) *Central, femic, mainly effusive, ophitic.* This term I have used to denote a texture in which augite acts as cement or matrix and large patches often enclose idiomorphic feldspar in which the lateral pinacoid (brachy-pinacoid) is best developed and often the direction of the brachy-axis. An important feature of this texture is the fact that the feldspar has its form sharply developed against the augite. A. N. Winchell is inclined to lay the main stress upon this and thus broaden the use of the term ophite. His authority for so doing is derived from the first paper of Michel Lévy,[11] introducing the term, in which he uses the term ophitic. His arguments for his usage are given in the Bulletin of the Geological Society of America, Volume 20, pages 661 to 666. On the other hand I published quite a discussion in a foot-note on page 227 of the Isle Royale Report, of the two definitions, and in the Bulletin of the Geological Society of America, Volume 18, page 648, I gave a short note on the ophitic texture to accompany some illustrations from lantern slides of the ophitic texture as I understood it as a variety of the poikilitic, following the definition given by Michel Lévy in his "Structures et Classification des Roches Eruptives," page 28. The facts seem to be that Michel Lévy has used the term in a broader and in a somewhat narrower sense and that there has been fairly continuous use by two schools,—one using it in the narrower sense which will be found quoted on page 227 of the Isle Royale report. I translate it. "When the last element consolidated is a bisilicate (generally pyroxene) its areas without their own proper exterior form are larded with older crystals. Those of the feldspar notably are elongated in the direction of the edge between (001) and (010) and are flattened parallel to (010), and the ensemble takes a characteristic appearance which I have described and figured since 1877 under the name of ophitic texture." In the earlier paper upon which Winchell relies we find that more stress is laid upon the

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

fact that the pyroxene "moule"[12]—acts as a mould or matrix for—the feldspar and the relative size of the two is not mentioned at just that point.

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

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

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

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

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

The probabilities are that it will be found a rather desirable thing to emphasize the relative size of the feldspars and the pyroxene and if ophitic in the broader sense is to be used to replace

[12]Fits the feldspar as dress of the present fashions fit the female form. I notice the word used in that connection in French. A. C. L. 1909.
[13]Loc. cit. p. 169.

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

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

The augite seems to drive the corroded remnants of olivine before it in its growth. I suppose, too, that any interstices which were left would be between the different crystals of augite which seem to have been the last consolidation in a typical ophite. Thus when the rock is altered or exposed to weather the centers of the au-

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

gite patches are the last to be affected and are left as knobs on the weathered surface as shown in Plates II and III of this report (see also Vol. VI) and as may be readily seen almost anywhere on Keweenaw Point but especially well on the Greenstone Range itself. This same knobby appearance is very characteristic at Mamainse in a heavy bed on the north side of Sand Bay. On matte surfaces, such as pebbles or joint planes or diamond drill cores there is also a mottling,—the augite centers being often somewhat lighter as seen against a darker green chloritic or reddened ground (Pls. IV and VI) but the exact color pattern may vary. The weathered portions may sometimes be browner. One can thus with a little

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

training recognize without any thin section the gradual increase in grain of the augite, and the rocks which show this mottling are very monotonously the same, even under the microsope differing, so far as I can see, but slightly. Some have a little more or little coarser olivine remnants. Occasionally this ophitic texture may be combined with large feldspar phenocrysts (eocrysts). This is true sometimes in the foot of the Kearsarge lode and occasionally in the Greenstone itself.

A very good large colored diagram of the ophitic texture is given

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

(b) *Doleritic* (Pl. VII, Sp. 17998). This term I used in the Isle Royale report for a texture in which the feldspar was much coarser relative to the augite than is generally true in the ophite. The term *doleritic* has always been applied to rather coarse grained rocks of the basaltic and diabase families. A recent suggestion has been to apply it to rocks of these families in which the feldspar can be easily recognized with the eye or the lens, while hornblende or pyroxene cannot. This is the definition suggested by Iddings, Chamberlin and Salisbury in their Geology, Volume I, p. 417, and adopted by Pirsson ("Rocks and Rock Minerals," p. 198). It is obvious that my definition of the texture is not out of harmony with this macroscopic definition since if the feldspar could be recognized and the pyroxene not, it would be likely that the feldspar would be relatively coarse, though perhaps not really in larger grains than the augite, since it is easier to recognize feldspar with characteristic twin striations than to separate augite from hornblende. It is, however, true that I have applied the term "doleritic texture" and "doleritic streaks" in my descriptions of the cross-sections (cf. Isle Royale, drill hole III, Sp. 15126) to specimens which Pirsson might call "gabbro," e. g., that figured in Plate VII, that are so coarse that both the feldspar and the augite can be distinctly recognized by one who is practiced. The fact is that one will find in the heavier beds (more frequently in some than in others) streaks which appear to be almost sharply separated from the rest of the rock. In many cases they might readily be taken for intrusions and yet if one will study one will find that there is a definite connection between their coarseness and the coarseness of the surrounding rock, and that they never occur very close to the margin,[16] and will, I think, finally conclude that they are due to some sort of differentiation by which some of the ingredients have gathered together in the process of cooling and produced a magma more favorable to the coarse crystallization of the feldspar. This may be due to some such action as that which produces a stratification banding in water with very finely divided clay slowly settling in it,

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

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

but I am more inclined to think that it is due to the accumulation of some sort of mineralizer, say water vapor, or the like, in certain layers. There may be a distinct tendency toward separation of the water bearing and non-water bearing magma. In some of the large exposures of the Greenstone, say back of the Central mine, one will find broadly curved bands of lighter and darker color, which appear like the stratification of some gneisses, but these are evidently nothing more than eutaxitic flow lines, possibly marking some initial slight difference in temperature which has been rendered permanently visible by slight differences in the abundance of certain crystals. The phenomena are very well described (and without any such theoretical preconception as might tempt me to warp my account), by Marvin in his description of the light and dark kinds of diorite by which he cuts the "Greenstone" up into the different beds of his Eagle River section 91 to 108.[17] All of these belong to one immense flow. That feature Marvin does not seem to have grasped. He describes two types,—the light type and the dark type, and these alternate over and over again. Beds 90 to 91 represent the finer grained ophite near the margin and Beds 92 and 93 a coarsely mottled rock of the ophite type; from Beds 94 to 106 there is a pretty regular alteration of what he calls the "light type" and the "dark resinous type,"—the light being what I should call "doleritic," the dark resinous type being the "ophitic" or "luster mottled." This is, however, the coarsest possible illustration of the texture in a rock which might be by many considered as a gabbro, *but if so it is an effusive gabbro.* The feldspar here in the light type is long and, as he says, at times over an inch in length. The plagioclase twinning lines are so coarse that he noticed them. He suggests that the relative proportions are 40 to 54% feldspar, about 40 to 46% (he calls it hornblende) augite, and considerable delessite (including the altered olivine?) It has a coarse crystalline, irregular texture with numerous segregations of coarser material composed of prehnite and feldspar and quartz and epidote, all suggesting a rock originally rather porous, and my explanation is that in the process of the crystallization the gaseous mineralizers, being collected in certain streaks, produced a coarser crystallization of the feldspar and a more open miarolitic or interstitial character. These interstices may be lined with borders of fibrous chlorite or chalcedony. The main filling may be as described by Marvin or the interstices may be filled with chlorite and quartz, apatite needles, and various specks

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

of iron oxide. Against them not only is the feldspar sharply bounded by the augite but may often be seen to have its crystalline form. Figure 7 of Report for 1903, herewith reproduced as Figure 17, illustrates this, and Figure 3, Plate VI of Volume VI which is a photograph, not a drawing, shows the same thing, not so sharply and more or less disguised, with a tendency toward an agglomeration of the feldspar. Close to the center of the field and a little down to the left is a cavity between three fairly large feldspar crystals which is lined with the fibrous chlorite rind. The filling of these interstices might properly be called secondary but in some cases, no doubt, the filling began long before the rock had lost its original heat. Indeed, it may have been pretty closely associated with the original cooling. If I am right in thus regarding these streaks and this texture it is a superficial equivalent to deep-seated pegmatites and similar rocks. The tendency to this doleritic texture seems to be characteristic of some beds more than of others and these doleritic streaks appear at times to be fairly persistent. Some engineers have correlated from drill hole to drill hole by them, but if I am right as to their origin such a correlation is unsafe. Yet their presence is a pretty sure sign of a rather heavy flow and correlation can often be made by this fact.

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

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

	Thickness of flow.	Distance to margin.	Length of grain of feldspar.	Location.
Central Mine:				
Bed 112	205	6	2- 3 mm.	d. 7.648
Bed 116	270	81 100	6- 8 mm. 10 mm.	d. 7.804
The "Greenstone" Manitou Section 3 N. (Fig. 29)	1130	*	3 mm. 6 to 8 5 mm. 6 to 8	d. 3.74 3.99 3.161 3.220
Sp. 17998			12	255
Mandan Ophite	475	116 172	4 mm. 10 mm.	d. 12.136 192

* About same as depth in hole.

(c) *Glomeroporphyritic or navitic.* (Pl. VII, Ss. 15384, 15295). The appearance under the microscope of this texture is illustrated in Figure 4 of Plate VI of Volume VI and also in Rosenbusch's Figure 1 of Plate IV of Volume II, though that is not really highly characteristic. In Irving's Monograph, Plate IX, Figures 2 and (especially) 3 this texture may be represented. It is characterized by the fact that the feldspar occurs with very considerable range of size and the larger feldspars tend very strongly to gather together into bunches or clots. To this the word *glomeroporphyritic* applies, which we may paraphrase as agglomerated porphyritic or clotted. Iddings well calls it seriate porphyritic. The origin of the texture seems to be in the fact that there was a considerable excess of feldspar molecules in the cooling magma so that the feldspar crystallized before the magma came to rest, and grains stuck together more or less. The feldspar growth seems to have been continuous and these larger feldspars which rolled in from perhaps a cooler point in the course of the flow may be toward the margin considerably larger than in the grain which would result from the very last consolidation. (Cf. Pl. VII.) In a glomeroporphyritic flow there may thus be a very considerable hiatus between the two kinds of feldspar near the margin and an almost continual series toward the center with every gradation between what Iddings calls the seriate and hiatal fabric. These feldspars do not seem to be radically different in chemical composition or widely separated in time of origin from the latter feldspars. Nor are they generally speaking corroded. They are what I have called rhyocrystals and not brotocrystals. Larger and distinctly hiatal crystals with no transition to the crystals of the ground mass do, however, occur and are characteristic of certain beds. One of the most important

of these is the foot wall of the Kearsarge lode. (Pl. VII, Sp. 17956, and Mandan d. 18 at 90 ft.) The glomeroporphyritic is a type of texture which occurs especially in the Ashbed series; for instance, in the beds near the Pewabic worked by the Quincy mine, but some signs of this texture occur all through the series in many of the more feldspathic melaphyres, especially in a group below the Wolverine sandstone in the Central mine section, Beds 97-115, in the Torch Lake Mining Company section, Beds 30-59, Holes 4-7.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

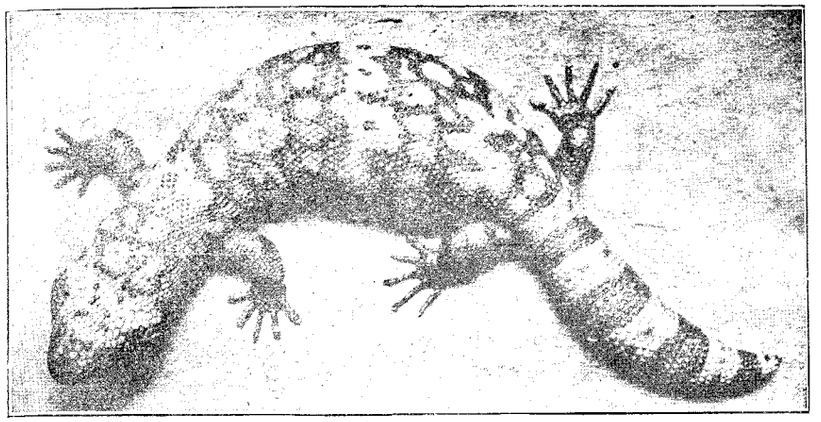
Ss.	15000-16000	are from Isle Royale and mainly sectioned. The sections are in the Ashbed and Central Mine group of flows. Up to 16400 they were also from Isle Royale, mainly not sectioned.
Ss.	16401-16473	are from Tamarack No. 4 shaft. Down to 16445 mainly Ashbed group, down to 16457 above con- mainly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

Ss.	17636-17653	are from Franklin Jr. cross-cut (See 20429). Figure 40.
Ss.	17654-17686	are from Tamarack 5 shaft.
Ss.	17686-17689	are Gratiot Bluff felsite.
Ss.	17690-17695	are near South Range near hill north of belt.
Ss.	17695-17715	are various specimens in Ontonagon district, a
Ss.	17715-17865	few of them sectioned. 17705 is a glomeroporphyrite.
Ss.	17866-17871	Copper vein, prehnite, melaphyre boulder.
Ss.	17878-17899	Atlantic Mine cross-cut. Chapter V, § 16.
Ss.	17899-17991	Franklin Jr. (See 17342) section and drill holes sections Nos. 17982, 17991. Figure 40.
Ss.	17992-17999	Drill cores, Manitou holes.
Ss.	19401-19703	are between Winona and Rockland, described by P. S. Smith, typewritten. A few thin sections have been made with notes by Lane.
Ss.	19704-19775	West of Ontonagon.
Ss.	19735-19740	Old Colony cross-cut. Chapter V, § 10.
Ss.	20039-20340	Black River section with Gordon's notes. (Report for 1906.)
Ss.	20351-20354	Ashbed group on south side of Portage Lake, Section 35, T. 55 N., R. 34 W.
Sp.	20356	Sectioned eastern sandstone, Wyandotte drill hole 13. Chapter V, § 21.
Sp.	20357	Amygdaloid conglomerate, Wyandotte drill 9.
Sp.	20358	Sectioned, epidotic sediment, Wyandotte drill 5.
Sp.	20359	Section of datolite, Winona Mine.
Ss.	20380-20427	Superior trench and shaft. Chapter V, § 14.
Ss.	20429-20442	Franklin Junior, 4th level cross-cut, of Section 17653. Ch. V, § 11.
Ss.	20443-20446	Franklin Junior, 21st level cross-cut. Ch. V, § 11.
Ss.	20447-20458	Miscellaneous illustrative specimens from various locations.
Ss.	20461-20485	Manitou section.
Sp.	20485	M. 3. 122.
Ss.	20486-20500	Mendota ophite and intrusive felsite porphyrite.
Ss.	20501-20559	Mount Bohemia.
Ss.	20560-20562	
Ss.	20563-20598	Torch Lake sections, 20575 Minong type. Ch. V, § 10.
Sp.	20600	Altered boulder of Calumet and Hecla.

Sp. 20601 Copper and silver from Old Colony lode.
Sp. 20602 Calcite and copper in two generations.
Ss. 20617-20620 Diamond drill core set, used in Plate VI, from St. Mary's Challenge exploration.
Ss. 20623-20638 Calumet and Hecla White Pine explorations.

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

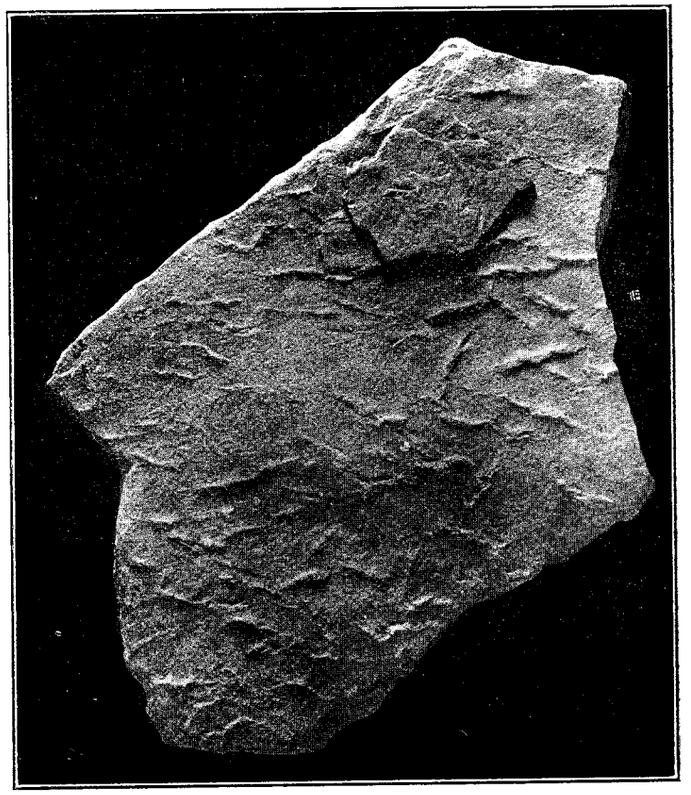
Sp. 19086
Sp. 17982 Steamed sediment.
Sp. 17998 (Oligoclase Ab An.). Into the hanging of the Pewabic Lode.
Sp. 20356 The earlier sandstone. Marvine's Conglomerate 6-8, or sediment.
Sp. 20358 Wyandotte Hole 5 at 307.
Sp. 20359



(A.) PHOTOGRAPH OF AN OPHIDIAN, THE GILA MONSTER, TAKEN BY JESSE MYERS OF THE ZOOLOGICAL DEPARTMENT OF THE MICHIGAN AGRICULTURAL COLLEGE.

(B.) OPHITIC MOTTLING BROUGHT OUT NEAR A SEAM OF CHLORITE FROM THE MANITOU SECTION 3 D. 3 N., AT 543 FEET DEPTH; IN THE GREENSTONE, THE BASE OF WHICH IS ABOUT 72 FEET AWAY. THE DIAMETER OF THE CORE IS 7-8 OF AN INCH.

(C.) THE EFFECT OF OPHITIC TEXTURE IN THIN SECTION, HALF-TONE REDUCTION OF PLATE IX, MONOGRAPH V, U. S. G. S., BY R. D. IRVING. FROM A MELAPHYRE IN THE SOUTHEAST QUARTER OF SECTION 9, T 51, R 12, MINNESOTA, ENLARGED ABOUT 4.7 IN DIAMETER.



TRACKS (?) ON SLAB OF NONESUCH SHALE, PHOTOGRAPHED BY J. T. REEDER. DIMENSIONS OF SLAB ABOUT 10 X 14 INCHES.

CHAPTER IV.

THE GRAIN OF THE IGNEOUS ROCKS.

§ 1. INTRODUCTION.

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

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

The Keweenawan rocks most often occur in dikes, sills, sheets and lava floods,—forms, one of whose dimensions is so much less than the others that the position and distance from the margin in this direction is the important factor. It is not the only important factor, for the chemical character is, of course, of fundamental importance. The more viscous (practically the more feldspathic) the magma, the finer grained. The process of growth may be stopped in one of two ways, either the available molecules are exhausted or the magma becomes so viscous that they can no longer be pulled out. In the former case it may be simply that the rock is all consolidated and wholly crystalline, the mineral in question being the last one formed. It may also be that the remaining molecules are soluble at a given temperature and pressure and may go into entirely different crystal molecules, and indeed the crystals formed

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

may be redissolved. For instance, we find plain indications in the Keweenawan rocks that a magnesium silicate forms as olivine at high temperatures, but that if the part molten rock remains near certain lower temperatures long enough the olivine already formed may be corroded and augite molecules formed instead. Thus for a certain distance in from the margin the olivine may be sharp and conspicuous, and farther in may be only in corroded grains.

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

The retention of solvent gases seems, as we have mentioned in discussing the doleritic and ophitic or poikilitic texture, also to aid the power of feldspar crystallization, so that the last formed feldspar is likely to be coarse relative to the augite in intrusives, pegmatites and doleritic streaks. On the other hand, it appears that the surface melaphyres flowed and kept pretty well stirred up in temperature until they were cooled to within 10 per cent of the crystallizing point of augite, and that consolidation took place from the margin to the center before the center had cooled much,—for the grain of the augite (as theory would lead us to expect in such a case) increases from the margin to the center. Theoretically, we should find that there could be a rapid rate of increase proportional to the distance from the margin for a short side zone which was crystallized before the adjacent rock had heated up appreciably and there would then be a transition (fairly sharp) to a slower rate of increase. This, if the degree of superfusion is small, and the initial temperature not over 5 per cent more than the crystallization temperature, will continue from the margin to the center and be proportional to the distance from the outer margin of the contact zone. The augite of the Keweenawan melaphyres which crystallized really followed these laws to a rough degree of numerical accuracy. The contact zone and rapid rate of increase is confined to a belt usually less than ten feet. The inner rate of increase (which I have called A, the outer C′) is fairly uniform for any

one flow[2] and in the lustre mottled melaphyres or ophites is usually between 1 mm. in 10 and 1 in 20 feet, or say 1 mm. in 3 to 5 meters. In the more feldspathic flows, like the Kearsarge foot, it is less. The maximum rate of increase must depend on the ratio of viscosity and consolidation. The very highest inner rate of increase is a rate of 1 mm. for each 8.5 feet, but in the large majority of cases the rate comes out 1 mm. in somewhere between 11 and 16 feet. This refers to the linear diameters of the augite grains as indicated by the mottlings on the drill cores. (Pls. IV and VI.)

§ 2. GRAIN NUMERICALLY DEFINED AND RECOGNIZED.

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

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

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

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

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

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

tions, for by adding them and pointing off two places one can get the average dimensions in mm. at once.

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

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

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

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

§ 3. GRAIN DEPENDENT ON RELATION TO THE MARGIN.

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

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

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

This second factor is the rapidity of crystallization or linear velocity of growth of crystals in millimetres per minute. This differs in different directions. We ordinarily assume that the planes of cleavage are planes of greatest molecular density. It is natural to infer that in attractions lying in these planes the molecular attractions will be strongest and there will be a tendency to greater growth. This is, indeed, true in a general way. Minerals which

[4]Tammann, G., Kristallisieren und Schmelzen, 1903, pp. 134, 140, 161.

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

This velocity of growth must depend upon the rate at which molecules can be drawn in, and this in turn must be diminished by the viscosity,—the internal friction of a fluid. The viscosity of a fluid is, indeed, measured in just this way, by the velocity

with which steel balls will move through it drawn down by the attraction of gravity.

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

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

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

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

It may be proved experimentally and theoretically that the slower the loss the coarser the grain, and in particular the slower the cooling the coarser the grain. And it may also be shown that the less the drop, that is the less the difference in conditions between those of crystallization and those of the country rock toward which the molten mass is cooling, the slower the cooling and hence other things being equal the nearer the country rock is to melting the

[5]Kristallisieren und Schmelzen.

coarser the grain. Examples of slow or slight change of conditions and coarse grain are rock candy and rock veins. Pegmatite must be another. Agate cavities have walls lined with relatively rapidly precipitated silica. Often at the center is quartz in larger crystals, more slowly formed as the supply became slower and slower.

Diffusion and loss of gases or mineralizers follow laws like those which apply to the loss of heat. The fundamental principle is that

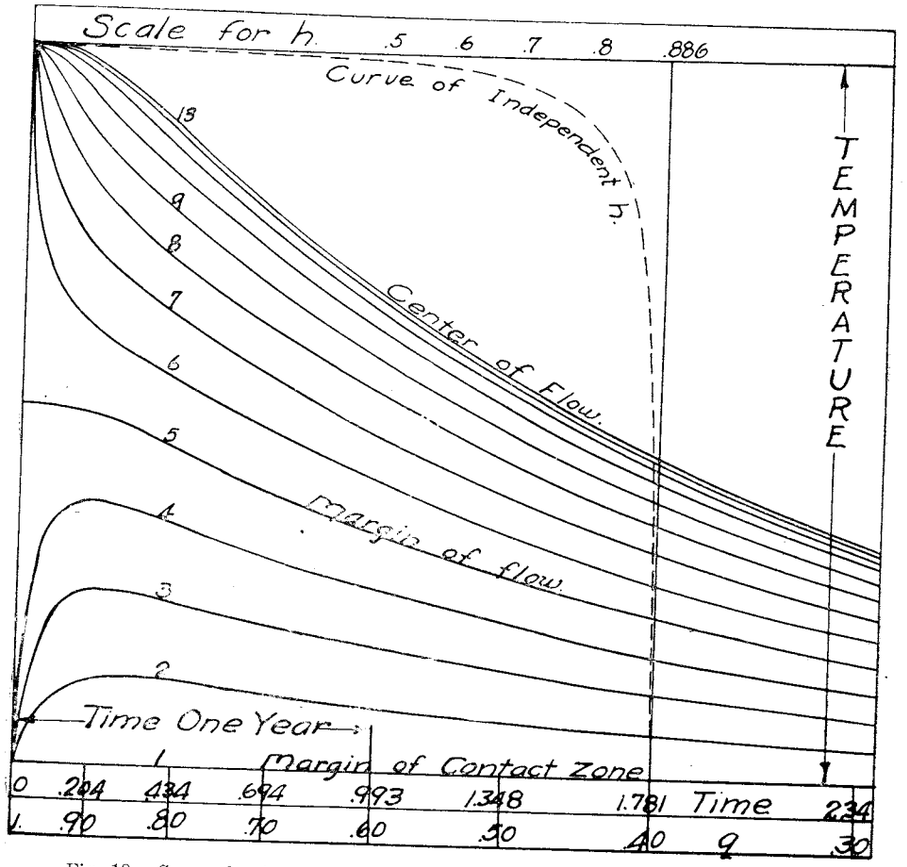


Fig. 18. Curve showing cooling of lava sheet and heating of a contact zone supposed to be one-fourth the breadth of the lava sheet on either side. The abscissa (x) represents the time, the lapse of which is measured from left to right. The temperature for different times is given by a series of curves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

if there is at a given point a change of state (for instance, loss of temperature) in time there must be not merely a steady flow, as much transmitted as received, but an accelerated flow or change in space, the amount transmitted being increased over that received by the amount lost.[6]

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

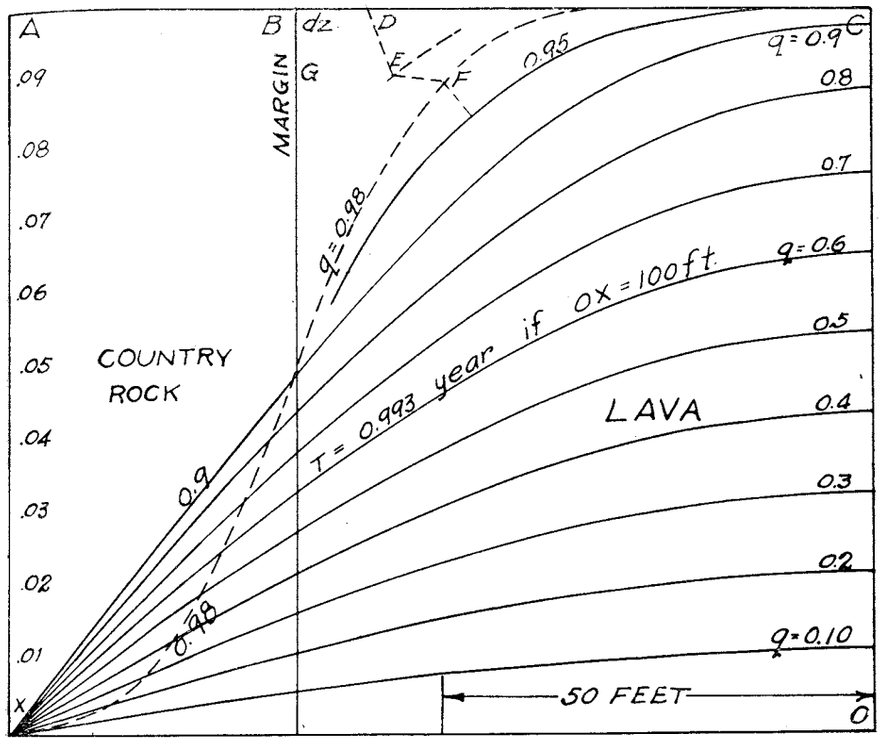


Fig. 19. Shows the cooling of the same igneous sheet as Figure 18 with the temperatures as ordinates but the distance as abscissa, the curves being given for different epochs of time not equally spaced. It may thus be considered as a view of the same surface as Figure 18 looked at from the right hand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

The curves showing the temperature at any given time of an indefinite cooling sheet placed between two others which are allowed to heat up but kept at constant temperatures outside can be plotted without any serious difficulty if we suppose diffusivity to be con-

[6]In mathematical notation this statement becomes

$$du/dt = a^2\ d^2 — u/dx^2$$

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

stant. Such curves I have given among other places in the Isle Royale report (Vol. VI) and in the annual report for 1903 for three different widths of the outside sheets.[7] In this report I give a slightly different set showing the cooling in case the outside sheet, the belt supposed to be heated at the margin, is one-fourth of the total thickness of the hot sheet of rock and one-sixth of the total thickness supposed to be affected. To show the connection between the three variables, temperature (v), the position in the sheet and its distance from the margin (x) and the time (t) requires really a surface which may be represented by contour lines and in Figure 18 and Figure 19 I have given two views of the surface, one in which the abscissa is the time and the ordinate the temperature and the contour curves are equally spaced distances from the center of the flow. In the second figure the abscissa represents the distance from the center of the flow and the ordinate the temperature as before while the curves represent different, *not equally spaced* epochs in the cooling.

§ 4. CRITICISMS.

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

As to the disturbing effect of undercooling and the latent heat given out in crystallization there are certain factors which may

[7]In the curves figured by Queneau and copied unfortunately by Iddings the abscissas are not proportional to the time, but to a function thereof.
[8]Petrogenesis, p. 45.
[9]Natural History of the Igneous Rocks, pp. 219-221.

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

§ 5. ALLOWANCE FOR VARYING DIFFUSIVITY.

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

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

initial layer (BD) the ordinate curves instead of being straight lines and parallel to the vertical axis will vary as DEF shown in the figure and will give us then the corresponding thickness.

If then we take our uz curves for the solution of

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

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

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

§ 6. MATHEMATICAL TREATMENT.

General Formulae for Rock Grain.

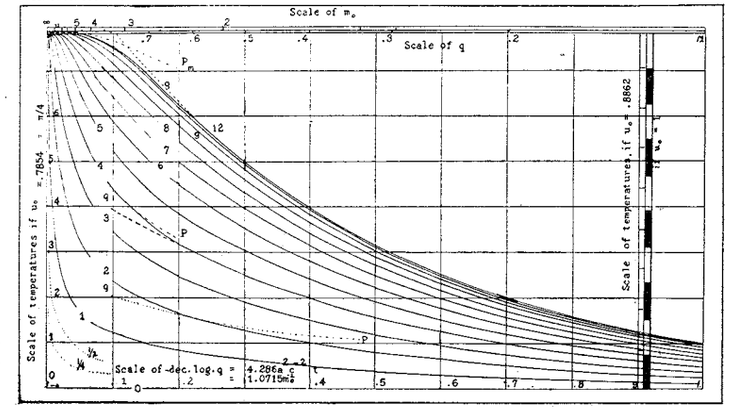
Marginal Temperature Fixed.

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

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

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

BULL. GEOL. SOC. AM. VOL. 14, 1902, PL. 54



CURVES OF COOLING—MARGIN TEMPERATURE CONSTANT

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

$$(1) \quad \frac{u}{u_o} = P_m - (P_{m_o+m} - P_{m_o-m}) + (P_{2m_o+m} - P_{2m_o-m}) \ - - -$$

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

where:

u is the temperature after a certain time (t);

u_o is the initial temperature;

t is the time from the beginning of cooling;

x is the distance from the margin;

c is the thickness of the flow;

a^2 is the diffusivity,

$m = x/2a\sqrt{t} = x\, m_o/c$

$m_o = c/2a\sqrt{t} = c\, m/x$

$\text{nat log } q = -\pi^2a^2c^{-2}t = (\pi/2m_o)^2$

$P_m = \frac{2}{\sqrt{\pi}}\int_o^m - m^2dm$ is the probability integral of which there are numerous tables. The report for 1903 and Johnson's "Theory of Errors" contain them.

$\pi = 22/7 = 3.1416$

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

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

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

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

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

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

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

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

$$(4) \quad h = \sqrt{\frac{-d\,(m)/m^3}{-d\,(u/u_o)/(u/u_o)^3}}$$

Then (3) may be written[4]

$$(5) \quad g = \frac{c\,k}{a\sqrt{u_o}} \cdot \frac{x}{c} \cdot \frac{1}{h\sqrt{2\,(u/u_o)^3}}$$

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

[2]See Byerly, Fourier's Series, Article 60, ex. 1.
[4]The steps are somewhat more fully given in the report for 1903.

VALUES OF h BEFORE CENTER HAS COOLED.

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

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

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

$$(6) \quad g = C'x \text{ where } C' = \frac{k}{a\sqrt{u_o}} \cdot \frac{1}{h} \cdot \frac{1}{\sqrt{2\,(u/u^o)^3}}$$

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

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

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

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

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

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

E then should really vary between the value of g derived from Eq. 6 if the increase kept up to the center, that is $\frac{C'c}{2} = \frac{c\,k}{2a\sqrt{u_o}} \cdot \frac{1}{h} \cdot \frac{1}{\sqrt{2\,(u/u_o)^3}}$ and the value just found in (8) which does not depend upon the initial temperature u_o. The

ratio of these two is also the ratio of the distance from the margin at which the grain would be equal to that at the center if the marginal increase kept up (which we may call the belt of marginal increase) to the distance from the margin to the center. It is

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

Cf. Figure 21 below.

Marginal Temperature Not Fixed.

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

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

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

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

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

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

$$(15) \quad v = \tfrac{1}{2} (u\, x' + 2\, y + u\, x')$$

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

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

At the Center.

Here

(10) $v = u_w$ whence we have

(11) Center grain

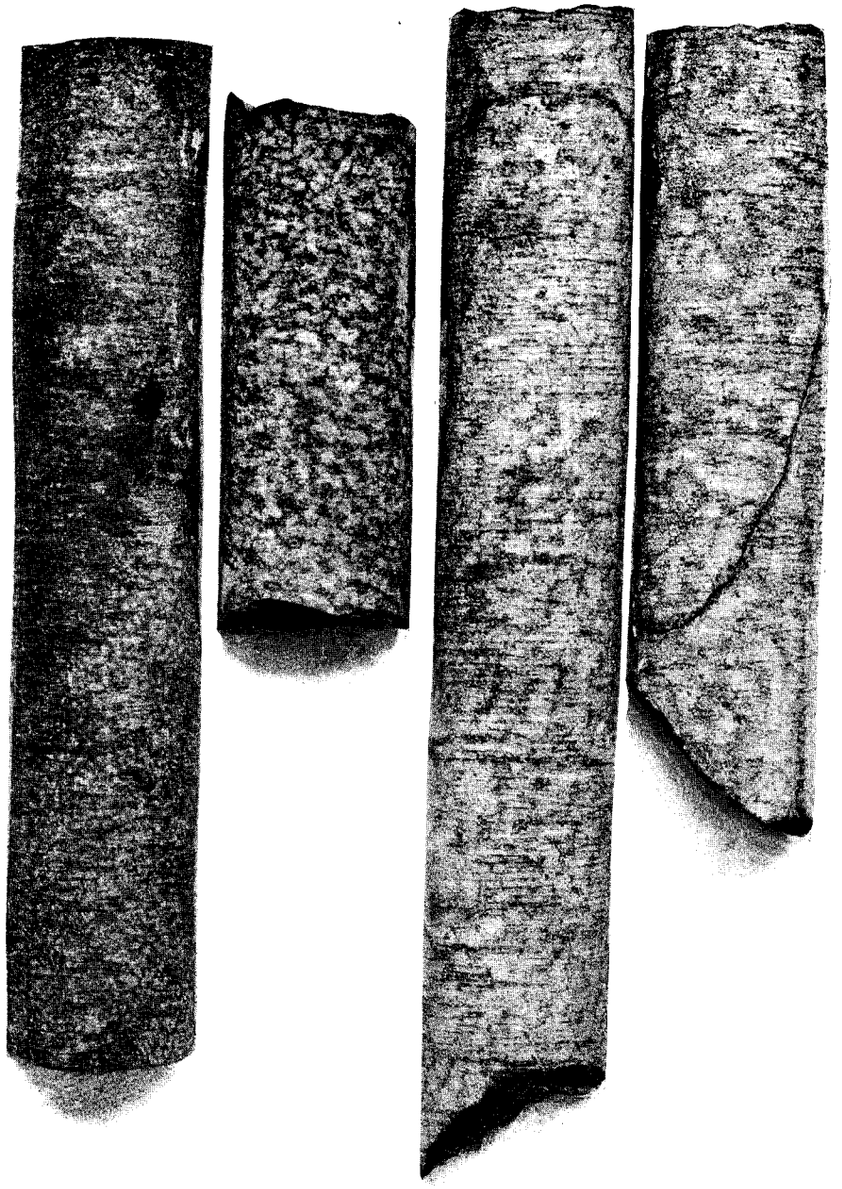
$$g\,(k, x' = c/2, v, u_o, y, c) = g\,(k, x = w, u_w, u_o, y = o, c.)$$

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

PLATE VI.

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

The cores are arranged with that nearest the bottom at the extreme left, as follows: 20620, 20619, 20618, 20617. Depth in drill hole 250, 232, 202 and 172 feet. Distance from margin at 257 feet, 4, 13, 28, 43. Apparent grain 0.5 to 1, 1 to 2, 2 to 3, 3 to 4 mm. Thin sections 1.5 to .74, 2 to 1.34, 3 to 2.8, 4.5 mm. 20618 analyzed.



250 232 202 172

APPROXIMATE DISTANCE FROM MARGIN, IN FEET:

4 13 28 43

LUSTER-MOTTLING IN DRILL CORES OF OPHITES

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

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

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

At the Margin.

(Consolidation temperature nearer that of country rock.)

Here.

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

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

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

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

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

(Consolidation temperature nearer that of injection.)

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

(16) $g(k, x = x' + y, v, u_o, y, c) = g\left(k, x', v - \frac{u_o}{2}, \frac{u_o}{2}\, 0, 2w\right)$, where $2w = c - 2y$ and going back to equations (5) and (6) we find

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

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

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

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

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

Intermediate Zone.

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

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

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

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

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

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

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

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

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

and $v = u_y$

That is to say if the contact zone y is small enough so that $2\,v = u_{2y}$ becomes $0.33\,u_o$ before the center has cooled perceptibly, or the marginal temperature becomes say 1 / 6 of the initial, the cooling at that margin will be the same as at a corresponding point of the sheet of reference whose walls are kept cold. At the same

time the cooling at the center is the same as that of another point in the reference sheet, at a distance $\frac{c}{2} - y$ from the wall. The cooling on two planes, center and margin being the same as on two planes of the reference sheet, the cooling between must be the same, except that due allowance must be made for the different distance apart of the two sets of planes. The distance of corresponding planes being thus proportional we obtain a formula:

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

if 2 sin y π c = sin 2 y π c nearly.

At the center (23) reduces to formula (11) and writing $g = Ax' + B$ and the expression $(k\,c/a\sqrt{u_o})\,K$ comparing it with Eq. (3), and (5) we find

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

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

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

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

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

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

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

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

Approximate Formulae.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

The solution of this approximate formula as well as (in dots) curves representing more accurately the actual relation for three different breadths of contact in terms of $x'_{13} / c = E / C'\ c$ is given by the full line of Figure 21 (Fig. 6 of the annual report for 1903) repeated here for these values.

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

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

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

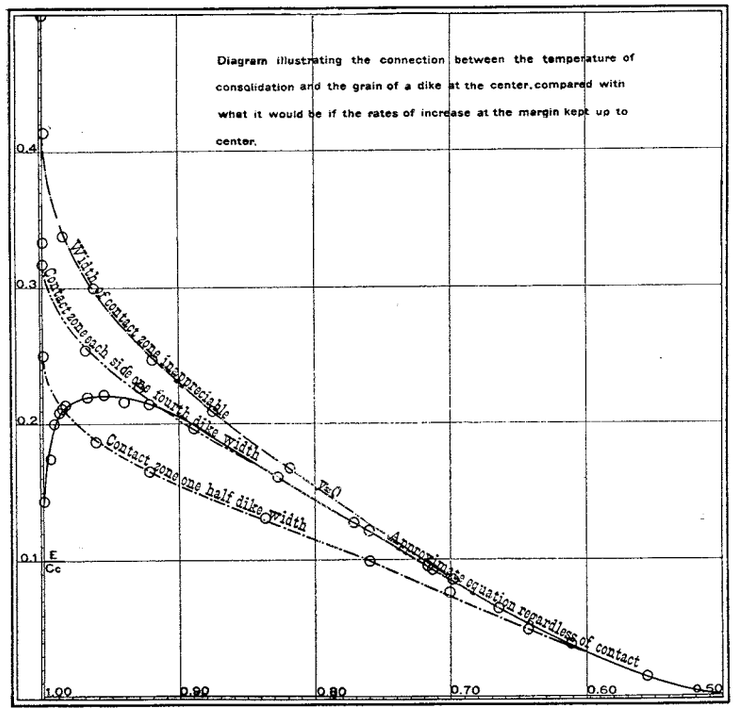


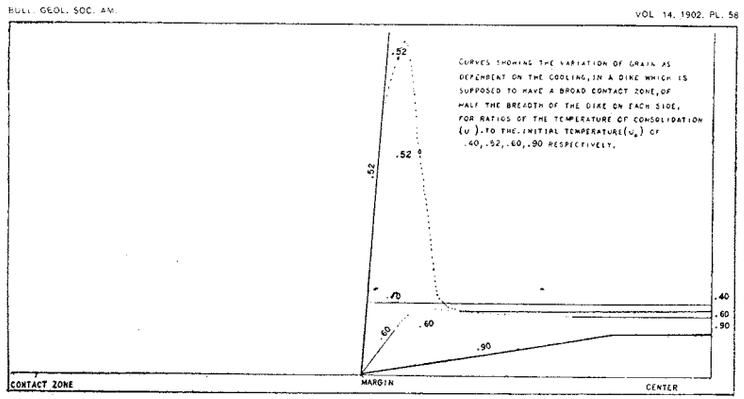
Fig. 21. S shows E / C′c, or the ratio of the grain at the center to that which would be reached if the rate of increase at the margin kept up for a distance equivalent to the whole zone affected. The full curve is the approximate solution given by equation 34 of the text. The dotted curves were computed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

Similarly

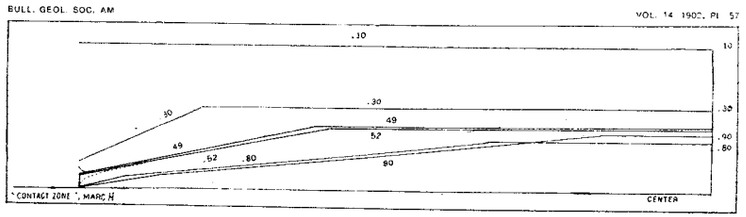
$$(36)\quad x'_{23} = (E-B)/A = .45\ hef^2 - y',$$

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

$$(37)\quad x'_{12} = B/(C'-A) = y \Big/ \frac{h}{2h'}\left(1-\frac{1}{2f^2}\right)^{-\frac{3}{2}} - 1.$$



(a)



(b)

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

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

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

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

$$(38)\quad y = \left(\frac{(2 \text{ to } \infty)\frac{3}{2}h}{2h'} - 1\right)x'_{12} = \left(1.4 \text{ to } \infty\ \frac{h}{h'} - 1_i\right)x'_{12}$$

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

$$(39)\quad \frac{C'}{A} = \left(\frac{h\sqrt{2}\,(2-1/f^2)^{\frac{3}{2}}}{h'}\right)\left(\frac{C-2y}{c-2y-2y'}\right)$$

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

$$(40)\quad \frac{C'}{A} = \frac{\sqrt{2}}{1 \text{ to } \sqrt{2}}\left(2-\frac{1}{f^2}\right)^{-\frac{3}{2}}$$

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

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

§ 7. APPLICATIONS.

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

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

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

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

There may be a belt of coarser grain than that at the center. It should be at the margin if the initial marginal temperature is just above that of consolidation. The higher the temperature of

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

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

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

Effusive rocks generally have broader marginal zones of grain

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

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

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

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

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

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

PRACTICAL APPLICATIONS OF OBSERVATIONS OF AUGITE GRAIN IN OPHITES.

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

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

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

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

4. If a variation in grain can be noted on two sides of a shaft, a cross-cut, or an outcrop, the direction of finer grain is probably that of the nearer amygdaloid or conglomerate, and the coarseness of grain will indicate the probable distance.

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

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

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

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

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

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

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

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

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

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

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