

IX above these points, but the top of No. IX is this very acid melaphyre porphyrite of a type which has not appeared above 426 feet in hole No. X. However, we should point out the strong resemblance of the rocks around No. X, 483 feet; No. IX, 385 feet; No. VIII, 47 feet, in order that any one may, if he choose, try his hand at making them the same horizon repeated. I have been unable to do so without assuming arbitrary faults *ad libitum*.

DRILL HOLE NO. IX.

	We then correlate the first 49 feet of No. IX with the bed of melaphyre already described (Ss. 15386-9). The next bed is—
54	49-103; (30 feet of drift not counted) (Ss. 15390-7); corresponds to
(53)	No. X, 483-508; (Ss. 15540-3). Melaphyre , porphyrite; red, finely porphyritic, with an almost felsitic matrix; with chloritic amygdules for the first 15 feet, then a grey trap like the flow above.
49	103-152; (Ss. 15398-402). Melaphyre , porphyrite; to the naked
(48)	eye much like the two flows above, though not so acid; at the top about 20 feet somewhat amygdaloidal (chloritic).
18	152-170; (Ss. 15403-6). Melaphyre , porphyrite; first ten feet red porphyritic amygdaloid. This bed has (at 164 feet) the same
(993)	decomposed green, light colored spots, as in No. X, 344 feet.
44	170-214; (Ss. 15407-8). Melaphyre , porphyrite; not very acid;
(43)	diabasic texture often conspicuous; red and amygdaloidal porphyrite at the margins.
8	214-222; (Ss. 15408-10). Amygdaloid ; epidote needles, etc., in the half-filled amygdules.
13	222-235; (Ss. 15411-2). Amygdaloid .
0	Seam or separation line of fine grained sediment .
44	235-279; (Ss. 15413-6). Melaphyre ; more or less amygdaloidal,
(43)	with laumonite and datolite.
(1,100)	
12	279-291; (Ss. 15417-24). Ash bed and scoriaceous conglomerate . The top of this bed is a very fine grained genuine ash, under which for a foot or more it is like a dark red sandstone. Lower we encounter a lot of laumonitic amygdaloid, and some samples which show more clearly its characters as a volcanic breccia, with intermingled sediment and scorix. It is much decomposed. Marvine's bed No. 63? Dips on drill cores 25°, 23°, with signs of cross-bedding.
(1,112)	
22	291-313; (Ss. 15425-9). Amygdaloid . Some of the specimens

(21)	look like ophites. They are all much decomposed, and it is barely possible they may all be part of the scoriaceous conglomerate.
15	313-328; (Ss. 15430-6). Conglomerate , scoriaceous. This contains green decomposed ash, and a calcareous cement. The three beds just described bear a striking analogy, in lithological character and stratigraphic position, to Marvine's beds No. 63 to No. 65, the "Ashbed" <i>par excellence</i> . One of the above conglomerates would be No. 17 of Marvine's plate, i. e., the Hancock West conglomerate. There is, however, a fault in the Eagle River series at this point, and I am not sure but that No. 64 and No. 65 are really the same bed. Marvine applies one and the same number to cover both the Ashbed and the underlying melaphyre. The relative position to the beds already correlated is just as it should be. (See table at the end of this chapter.)
57	328-385; (Ss. 15437-41). Melaphyre , porphyrite; like the porphyrite above 485 feet in No. X, already described. I think it is the same bed as the one at the top of No. VIII, down to 47 feet, which it is also like. We pass then at this point from the record of No. IX to that of No. VIII. But there is a peculiarity about the record of the rest of No. IX that deserves mention. After some feet of amygdaloids and clayey seams with some <i>copper</i> at 413 feet, No. IX finishes below 427 feet in a large bed of ophite, the like of which we do not find in No. VIII until we get down to 196 feet. Either, therefore, one of these two correlations (that of 385 feet in No. IX to 47 feet in No. VIII or that of 427 feet in No. IX to 196 feet in No. VIII) must be given up, or we must suppose a remarkable wedging out of intermediate beds, or lastly we must suppose that a fault has cut out part of the record of No. IX. But the correlations are—microscopic evidence and all else considered—very good. Moreover, in the interval, drill hole No. IX shows marked signs of disturbance, especially between No. IX, 385 feet, and No. IX, 427 feet. At 408 feet there is some kind of a break with much decomposed and prehnitic rock; at 413 feet there is a seam with <i>copper</i> ; at 420 feet a datolite vein; at 430 feet a brecciated amygdaloid. Therefore the last supposition seems most probable—that there is a fault. The character of a fault like the one here supposed depends upon whether the upper or the lower correlation gives the normal dip. If we assume as undisturbed the correlation 385 feet in No. IX, with 47 feet in No. VIII, and add to the difference (338 feet) the excess of elevation of No. VIII over No. IX (376.3-202.5, the altitude of the rock at No. IX; the surface of the ground is 30 feet higher) 174 feet, and divide by the distance between the holes
(56)	
(1,202)	

cores tend to be larger than those from correlations, and this fine grained sandstone furnishes some good observations. Three explanations for this want of agreement are possible,—

- (1) The drill holes may curve to the north. They are not likely under the circumstances, however, to curve in this particular way, and, if they did, the effect would regularly be more marked toward the bottom.
- (2) The conditions of deposit may have been such that the sandstone was formed in some measure by accretions, building from northwest to southeast, so that each of the laminae of which a bed was composed had originally a slight dip to the south greater than that of the bed itself as a whole. This is quite likely and is in harmony with the geological position of Isle Royale, with a mass of Archæan land to the northward of it.
- (3) The difficulty may be with the correlations, which may have been made to give too flat dips by faults not otherwise to be detected, which run between the drill holes and throw the south side up. This also is quite within the range of possibilities, and when we have the sum of the whole series we shall estimate what effect this might have.

This sandstone is a more thorough sandstone than any other in the series, of like size, and its course seems to be marked by a line of depression from Grace Harbor and its creek through to the northeast end of the island, as indicated upon the map. This bed is about (1565-1202) 363 feet below the bed (847 feet) that we have correlated with Marvine's Ashbed, No. 65, and would appear to represent the "first sandstone below the ashbed," which Marvine supposes to lie in a covered place, 506 feet stratigraphically below bed No. 65, which is about the usual (p. 68) rate of shrinkage between Isle Royale and Keweenaw Point. On this assumption the sandstone at No. VIII, 440 feet, just below, would do well for No. 85 of the Eagle River section, which Marvine seems to correlate with the "Pewabic West," and says is 767 feet below the slide above the Ashbed, and is No. 16 of his plate of conglomerates facing p. 60.* It would be wiser probably, and more nearly true to the facts, to correlate both our sandstones together as indicating a weakening in igneous activity represented by all the sandstones in the Eagle River section from bed No. 79 to bed No. 85.

- 11 420-431; (Ss. 15374-5). **Melaphyre**, porphyrite; about 4 feet amygdaloidal at the top (we are back to the porphyrites once more), dark green, with reddish porphyritic crystals. Matches Marvine's bed No. 82.

*Geol. Sur. of Mich. I, Pt. II.

- 0 431; **Sediment**; contact; Marvine's bed No. 83?
- 9 431-440; (S. 15376). **Melaphyre**, porphyrite; about 2 feet amygdaloidal at top; matches Marvine's bed No. 84, so far as size will permit.
- 4 440-444; (Ss. 15377-9). **Shale**, red. The grain is so fine that this bed was taken to be a fine grained trap until the microscope revealed its character.
- 1,589
- 42 444-486? (Ss. 15380-1). **Melaphyre**, porphyrite; very acid specimen; little olivine or augite, and might also be classed with the more acid rocks; amygdaloidal for 5 feet at the top, then a typical greenish grey trap. The exact bottom of this flow is a little uncertain. It lies on another flow of similar lithological character (both remarkable, under the microscope, for the scarcity of olivine), both of which appear to occur at the top of drill hole No. VII, to which we therefore pass at No. VIII, 486 feet, making the latter equal to No. VII, 10 feet. It is obvious that as the sandstones above No. VIII, 444 feet, do not appear in No. VII, the correlation of the top of No. VII cannot be sought above these sandstones. If we figure out the dip as before $(486-10) = 476$ minus the excess of altitude of No. VIII over No. VII $(262.6-376.3) 114 = 362$ feet, which divided by the distance, 1,584 feet, is 0.229, again the tangent of about 13° , (really about $0^\circ 5'$ less), only .002 from the tangent of the dip as computed between Nos. VIII and IX. So small a difference hardly requires any explanation. The boundary line between the two flows is not well defined; there may be a little faulting between No. VIII and No. VII, or the dip may vary a trifle from some other cause.

DRILL HOLE NO. VII.

- 73 102-83?; (Ss. 15283-8). **Porphyrite**; like the flow above, about 6 feet at the top amygdaloidal; has irregular amygdaloidal streaks, and occasional seams of laumonite; the porphyritic feldspar clumps are very well marked.
- (71)
- 26 83-109; (Ss. 15289-92). **Porphyrite**, amygdaloidal; *copper* in amygdules (at 83 feet), and in veins with prehnite (at about 90 feet); analcite and chlorite also occur in amygdules; the amygdules are often but partly filled, and lined with tufted chlorite and with white crystals. Laumonite also occurs.
- 0 109; Seam of **sedimentary** matter.
- 21 109-130; (Ss. 15293-4). **Porphyrite**, amygdaloidal; like the flow above, with alternating bands; more or less conspicuously porphyritic; possibly more than one flow; at 127 feet narrow vein of *copper*, prehnite and quartz.
- (20)
- 0 At 130 seam of **sedimentary** matter; much prehnite.

- 32 130-162; (Ss. 15295-6). **Porphyrite**, amygdaloidal, as above; at
 (31) 160 feet seam of *copper* in cubes, prehnite and quartz.
 35 162-197; (Ss. 15297-8). **Melaphyre**, porphyrite.
 (34) 197. Flinty-looking epidotic seam, a mass of **brecciated** prehnite
 and quartz. It will be observed that copper has been noted
 in four places in the beds immediately above, and that the
 amygdaloids are quite rich in minerals. It seems quite possi-
 ble that here at 197 feet is the center of the **vein** which has
 been a channel for this impregnation. There may be a fault
 here.
 2 197-199; (Ss. 15299-300). **Amygdaloid**. See petrographic chapter.
 0 199; (S. 15301). Seam of **sedimentary** matter; apparent dip 21°.
 11 199-210; (Ss. 15301-3). **Amygdaloid**; much decomposed, with
 zeolites, etc.
 11 210-221; (Ss. 15304-5). **Porphyrite**, amygdaloidal; like the rocks
 above near 130 feet.
 81 221-302; (Ss. 15306-15) **Melaphyre**; intermediate type, quite
 (79) feldspathic, yet in traces ophitic, with red feldspathic seams,
 and like Marvine's bed No. 87, which is one of Irving's types
 of the "ordinary olivine-free" diabase (Copper-Bearing Rocks,
 Mon. V., U. S. Geol. Sur., p. 65.)
 22 302-324; (S. 15316). **Amygdaloid**.
 (21)
 0 324; (S. 15317). **Vein** (possibly fault or contact); carries *copper*
 crystals, prehnite and quartz.
 13 324-337. **Amygdaloid**.
 0 337; (S. 15319). Vein and perhaps contact; carries *copper*, etc.
 (1,948)
 38 337-375; (Ss. 15318-20). **Porphyrite**, amygdaloidal; fine grained
 (37) and full of small chloritic amygdules and chloritic seams,
 which simulate bedding and may mark flow lines. Dip 17° to
 18° at 371 feet, 23° at 373 feet.
 19 375-394; (Ss. 15320-1). **Porphyrite**, amygdaloidal; analcite in
 cavities at 375 feet; generally fine grained chloritic amygdules.
 29 394-423; (Ss. 15321-4). **Melaphyre**; intermediate form, more
 (28) basic than adjacent flows, and somewhat ophitic.
 7 423-430. **Amygdaloid**. (It is not certain that S. 15324 does not
 belong to this flow.) I take this bed to be equivalent to No.
 VI, 74-81 feet, and we pass from No. VII, 430 feet, to the
 record of No. VI. While immediately below these points, in
 No. VII and in No. VI, respectively, there is a very peculiar
 bed of porphyry and felsite tufa, which makes the correlation
 a good one, the beds above this bed (i. e., above No. VI, 81
 feet and No. VII, 430 feet) do not match very well. This
 bed of porphyry tufa lies directly over the Greenstone, which

corresponds, as we suppose, to Marvine's beds No. 90-108 at Eagle River. Hence we should be at a point which according to our correlations should correspond to 1117 feet below the "slide" at Marvine's bed No. 63 and 431 feet more or less below the sandstone of Marvine's bed No. 80, while the corresponding thicknesses in our Isle Royale column are about 900 feet and 400 feet (see p. 66), rather greater than we should expect, for the increase in thickness of Keweenaw Point over Isle Royale is generally greater than this indicates.* We are led then to suspect faulting in No. VII, by which the series may have been duplicated. There are a number of places where faulting might occur in No. VII, but we have no means of determining its amount. Such faulting might account for the disparities between drill holes Nos. VI and VII, but the topography does not indicate any such fault, and it is easy to imagine that the Greenstone, which is very much thicker at Eagle River than in these drill holes, was so prominent at the former point that some of the immediately subsequent flows flowed around and did not cover the Eagle River part, while on the other hand they did cover Isle Royale. Mr. Stockly, however, reports a "break" as apparent near No. VII, running nearly south (and thus liable to pass between No. VI and No. VII), and throwing the east side down. Such a fault as that would, if it were a normal fault, hade to the east, and if it passed through the middle of drill hole No. VII, would not disturb the correlations and dips at all, but would cause us to leave out some beds unawares. In No. VII, however, the column as we have seen seems to be exceptionally full, so that we cannot attribute any great effect to the supposed fault. If it did not pass through the bottom of No. VII, and according to its strike it should not, the effect of such a fault would be to make the dip derived from correlations between Nos. VII and VI greater than it really is. But the dip derived from the correlation No. VII, 430 feet, with No. VI, 81 ft, is $(430-81) = 349$ feet plus the difference in altitude, $341-263 = 78$ feet $427 \div 1848$, i. e., $0.231 = \tan 13^\circ$, practically the same dip as found between No. VIII and No. VII. (p. 71.)

*See preceding pages, and end of this chapter.

DRILL HOLE NO. VI.

Above the correlation line we have—

0-17; (Ss. 15226-8). **Melaphyre**; shows occasional large porphyritic plagioclase crystals; is in general of intermediate type, like No. VII, 221-302 feet.

17-25; (Ss. 15229-30). **Porphyrite**, amygdaloidal; chloritic and laumonitic.

25-59; (Ss. 15231-3). **Porphyrite**, amygdaloidal; with chlorite or laumonite amygdules, white on red ground; occasional large porphyritic plagioclase; tubular amygdules at the bottom of bed.

59-67 or 72; (Ss. 15234-5?). **Porphyrite**, amygdaloidal; very porous; cavities lined with crystals.

72-81; (Ss. 15235-6). **Amygdaloid**. Cavities with fillings of radiating chlorite fibres.

10 81-91; (Ss. 15237-42). **Porphyry Tufa**. At the top there is a bed showing under the microscope the conchoidal forms of glass ashes, but in general the signs of sedimentation are very obscure, so much so that from mere inspection with the unaided eye I could hardly be sure that I was not examining a brecciated porphyry flow with some enclosures. This does not appear like a water-worn conglomerate, but like a contemporaneous tufa. It may be correlated with the "jasper," 67.7 feet above the Allouez conglomerate at the Peninsula mine (Hubbard, Proceedings L. S. Mining Institute, 1894, p. 93), and 460 feet down in Tamarack No. 1 shaft (Geol. Sur. of Mich., Vol. V, Pt. I, p. 112).

91-124; (Ss. 15243-7). **Ophite**.

33
(32)
(2,077)
239
(233)

124-363; (Ss. 15248-58). **Ophite**, the Greenstone. This is the largest single flow that we meet. It makes the "backbone" of the island, extending from Card Point to Blake Point in an almost uninterrupted ridge. Judging from the mottlings which are larger as we go northeast, and from the greater height of the ridge in that direction and from other reasons, the sheet thickens toward the northeast. This bed is distinctly lustre-mottled, and in sharp contrast with the series of porphyrites which overlie it and make a parallel ridge that extends from a low outcrop on the south side of Grace Harbor (including also part of Washington Island, further west), north of the Island mine, Siskowit Lake and Lake Richey, to the east end of Scovill Point. The backbone ridge thus agrees

in every way with the great corresponding ridge on Keweenaw Point, which is included in Marvine's beds of "diorite" (not having the use of the microscope, Marvine mistook augite for hornblende) Nos. 91 to 108, from 2927 feet to 4120 feet of the Eagle River section, which after personal inspection I pronounce a unit, the lighter and darker types being merely differentiations in the same flow. This is a colossal thickness for one flow (1193 feet), but I could find no finer grained band such as would mark a contact. Moreover, if we compare the size of the coarsest mottlings near Eagle River with those of the much thinner (233 feet) section of Isle Royale, some such great thickness is indicated. (See chapter V, on grain.) That we should find it thinner on the island is moreover in harmony with what we have hitherto found. This same Greenstone also thins very much toward the southwest along Keweenaw Point, as shown by Marvine, and by Hubbard (*loc. cit.*, p. 95). Moreover, both on Keweenaw Point and on Isle Royale, we shall find, in the series below it, similarly basic ophites predominating, while on the other hand the porphyrite type which has been so dominant above, from 589 feet to 2035 feet (1446 feet approximately equal to Marvine's 1272-2840, or 1568 feet) occurs only at intervals.

(2,310)

23

(22)

(2,332)

363-386; (Ss. 15259-66). **Conglomerate**; at the top a fine grained "ashbed," with a vesicular texture that appears to be due to contact with the overlying Greenstone; below 374 feet a more ordinary conglomerate, with acid pebbles of quartz porphyrites and felsites. There are also basic pebbles in it and the cement is calcareous. This must, according to our correlations, be the Allouez conglomerate, or the "slide" conglomerate, No. 15 of Marvine's plate.

We are now beneath the Eagle River section and for our correlations we shall have to use other sections, such as that of the Central mine, and the developments around Calumet.

8

386-394; (Ss. 15268-9). **Melaphyre**. This is a fine grained trap with no amygdaloidal top. Has it not been planed off by a fault? It is somewhat porphyritic, but tends to be ophitic at the center.

54

(53)

394-448; (Ss. 15269-72). **Porphyrite**, amygdaloidal; more or less amygdaloidal for 21 feet at the top and 12 feet at the bottom. This is really of the intermediate type with a doleritic texture in the middle.

64

(62)

448-512; (Ss. 15273-7). **Melaphyre**, ophite; not a very pronounced type; about 8 feet amygdaloidal with calcite veins; feldspathic; slight mottling. At this bed we probably pass over to the record of hole No. II.

(2,455)

DRILL HOLE NO. II.

As no conglomerate appears in drill hole No. II, its top bed, an ophite, must find its correlate at or below No. VI, 386 feet. Hence No. II must find for its first belt of amygdaloid, which occurs from 57 feet to 58 feet, a match in No. VI, not above 450 feet. The first such match is at No. VI, 512 feet, which we have adopted, since that will give us in each drill hole a heavy ophite above and a smaller one below. But if we compute the dip from this correlation, subtracting 512 feet in No. VI from 57 feet in No. II gives a difference of 455 feet. Adding the excess of altitude of No. II over No. VI (407 feet—341 feet), i. e., 66 feet, we have 521 feet, which divided by 2406 is 0.216, equal to $\tan 12^\circ 10'$. Thus we find too flat a dip, nearly a degree flatter than the last computation. If the dip were the same as previously (13°) or even steeper, drill hole No. II, 0 feet, would find its correlate at No. VI, 489 feet, or lower, but to say nothing of the fact that the beds in this case would not match as well, observations at the surface show that No. II is close to the top of the Greenstone or "backbone" ridge and cannot be very much below the great ophite, No. VI, 124-363 feet, which forms it. This of course favors as high a correlation in No. VI as we can get. The extra flat dip would then be due to a fault throwing No. VI up, but whether the fault strikes with the strike of the beds, and produces the ridge on which No. VI stands, or runs north, throwing the east side to the south, as analogy would render likely, or runs to the east, throwing the south side up and to the west, is not certain. It might pass through No. VI, near 393 feet. The upthrow, if 13° is the true dip, would be 34 feet.

0-57; (Ss. 15067-9). **Melaphyre**, ophite; rather feldspathic; in the exposures around the drill holes there are agate and laumonite amygdules.

7 57-64; (Ss. 15070-1). **Melaphyre**; fine grained, but of ophite type equivalent to No. VI, 512-523 feet, which may be more than one flow.

72 64-136; (Ss. 15072-5). **Melaphyre**, ophite.

(70)
0 136; (S. 15075). **Sedimentary** seam.

(2,532)
39 136-175; (Ss. 15075-9). **Amygdaloid** or **Conglomerate**. The samples of this bed were but scant as it is described as very rotten, and much of it was lost. At 167 feet a clay seam was noted. The samples are not sufficient to determine surely

whether we are dealing with an amygdaloid full of sandstone seams, or with a fault, or with a scoriaceous conglomerate. Possibly the Houghton conglomerate?

39 175-214; (Ss. 15080-2). **Melaphyre**, ophite. There is some doubt whether this is not one flow with the underlying.

(38) 214-271; (Ss. 15083-5). **Melaphyre**, ophite; about 9 feet coarsely amygdaloidal at the top, and 1 foot at the bottom.

(56) 271-325; (Ss. 15086-7). **Melaphyre**, ophite; about 14 feet amygdaloidal at top; at 315 feet and 320 feet, seams of decomposition, and then more amygdaloidal to bottom; carries laumonite and calcite.

(53) 325-365; (Ss. 15087-8). **Amygdaloids**; probably more flows than one; base ill-defined.

40 365-438; (Ss. 15089-91). **Melaphyre**, ophite; amygdaloidal at top, grey, and apparently not very basic.

(39) 438-475; (Ss. 15092-4). **Amygdaloids**, brecciated; very soft, so that we have only 17 feet of core for 38 feet of boring, probably a number of beds and possibly a fault. (Houghton conglomerate?)

(71) 475-556; (Ss. 15095-7). **Melaphyre**, ophite; top and bottom quite uncertain, but the massive mottled center is quite distinct; at about 554 feet becomes much veined, disintegrated, and prehnitic, with some *copper*.

(2,942) 556-570; (Ss. 15098-9). **Amygdaloid**, brecciated.

14 570-600 (?). **Melaphyre**, ophite (?); amygdaloidal; core about half ground away.

(29) 600-631; (Ss. 15100-1). **Melaphyre**, ophite.

(30) 631-650; (S. 15102). **Amygdaloid**; at 650 feet very much ground away and decomposed; a chance for a slide. Below this point No. II shows a massive, distinctly mottled ophite, all the way down (chlorite vein from 697 feet down to 700 feet), so coarse at the bottom that it is evidently considerably thicker, upwards of 70 feet thick. If this is repeated above, it must be either at 64 feet (the beds above 64 feet are too massive) or at 365 feet, which is possible, though there are reasons brought out by the microscope for believing this also not to be the case; moreover, the beds above do not harmonize. While there are several disturbed zones in No. II, there is no pressing reason, microscopic or otherwise, for supposing that a repetition in the series is shown.

When we turn to drill hole No. IV, we find a similar melaphyre at the very top. If we let No. II, 683 feet, be equivalent to No. IV, 0 feet (using the similar grain of the rock as an indication

that the two samples have similar positions in the flow), we have for the dip the difference, 683 feet, minus the difference of altitude (407-194 feet), 213 feet = 470 feet, which divided by 1808 feet is 0.260, i. e., $\tan 14^\circ 30'$. Thus, either the dip has become steeper or the correlation should be higher up in hole No. II, or a fault separates No. II and No. IV, such that No. IV is thrown up. This last supposition I deem most likely, for there is a ravine just to the east of No. IV, through which such a fault, running north and south, might go. Moreover, tunnels No. II and III do not strike the same rock, as would otherwise be expected; the one is east and the other west of this supposed break. Drill holes Nos. V and II are about in the direction of dip from each other and the fault suggested would also throw up No. IV relative to No. V, which is what the topography and records suggest.

Tunnel No. VII is in ophite, with seams, red, white, clayey and chloritic, which may be matched anywhere along the middle of hole No. II, and do not throw much light on the correlations. Supposing the dip to be 13° , as it has been taken to be to the south, the corresponding up-throw of No. IV would be 52 feet.

DRILL HOLE NO. IV.

33	From No. II, 650 feet (Ss. 15103-7).
(32)	
40	to No. IV, 40 feet (Ss. 15155-7). Melaphyre , ophite.
(39)	
(71)	
68	40-108; (Ss. 15158-60). Melaphyre , ophite; about 9 feet of amygdaloid at top, with calcite and chlorite.
(66)	
0	108; (S. 15161). Sediment , basic; to the naked eye like a fine grained amygdaloid.
25	108-133; (Ss. 15162-3). Melaphyre , ophite; fine grained; at 122 feet, fissure with quartz crystals.
(24)	
2	133-135; (S. 15164). Sandstone , basic; the Calumet conglomerate (No. 13 of Marvine's table, opp. p. 60) should come about here. As the top of the bed below does not begin in an amygdaloidal streak, but is quite coarse, we must infer an erosion or a slide at this point.
(3,197)	
92	135-227; (Ss. 15165-8). Melaphyre , ophite; very ferruginous.
(90)	
18	227-245; (Ss. 15168-9). Amygdaloid , brecciated.
18	245-263; (Ss. 15170-1). Amygdaloid .

17 263-280; (S. 15172). **Amygdaloid**.

24 280-304; (S. 15173). **Amygdaloid**.

(23)

(75)
(3,363)

The above series of amygdaloids are very much alike, very soft, veined, red, and so much ground away that only about half the core was left; consequently the limits of the various flows are very uncertain. Prehnite also occurs in them.

304-424; (Ss. 15174-83). **Melaphyre**, ophite.

120

(117)

(3,480)

Clay seam at 313 feet, near which the rock is much decomposed, fissured and seamed.

10

424-434; (Ss. 15184-6). **Amygdaloid**, chloritic and laumonitic.

16

434-450; (Ss. 15187-8). **Amygdaloid**; porphyritic texture, which is common in the other amygdaloids, with *copper*, laumonite and prehnite.

(3,506)

156

(152)

450-605½; (Ss. 15189-96). **Melaphyre**, ophite; very feldspathic; the bottom of bed not reached at the end of the hole, but the grain has become finer there, indicating that we are more than half way through the bed and not more than about 18 feet from the foot. With this flow we pass to drill hole No. V, and the latter must overlap unless the dip is 20° , or unless there is a fault of about 150 feet. With a dip of 13° we should expect to find No. V, 0 feet, at No. IV, 436 feet; if the dip is 14° , then at No. IV, 462 feet, etc. But the ophites around the top of No. V are, judging either from their thickness as measured in the section, which might be affected by the numerous seams in No. V, or from the coarseness of grain, not as thick as the bottom flow in No. IV. Nor are they quite as feldspathic. The bottom of No. V, though it lies in a fissure, and the record cannot be made out clearly, is in coarse feldspathic ophite, which corresponds both to the bottom of No. IV and also to the top of No. I. Drill hole No. I lies on the northwest side of a ridge which rises from Washington River, and is composed of ophites like the Greenstone. No. I is 30 feet lower than No. IV and 2092 feet + 1293 feet, i. e., 3385 feet from it to the northwest, at right angles to the strike. Thus at 14° dip the top of No. I would be $(846+30) = 876$ feet below the top of No. IV, at 13° dip $(782+30)$ 812 feet below it. Thus there would be a gap of something over 200 feet between the bottom of No. IV and the top of No. I. But as No. IV ends in a coarse ophite and No. I begins in one, and as field observations show all the intervening rocks to be coarse ophite, and as drill hole No. V is altogether in the same, we may be sure that the apparent intervening gap, if any there be, is composed of ophite. But it is doubtful if there be really any such gap. The topography

of the Island conforms in general closely to its geological structure, and the thick ophite of the bottom of No. II could hardly fail to make a ridge. There is a ridge, the only one with which it might be correlated, and No. I is directly under the northwest side of it. Again, in No. V the only ophite equally coarse in just above 344 feet, and if we assume No. IV, 610 feet, to correspond to No. V, 344 feet, the difference in level in the geological column would be $(610 - 344 = 266)$, minus the difference in altitudes, $194 - 56 = 138$ only 128 feet, whereas if the dip is 14° , there should be a difference of level of $(1293 \times 0.2493) 324$ feet, indicating an up-throw of No. IV of (196 feet) about 200 feet. If the same amount of up-throw existed between No. I and No. IV, the gap in the record between them would be practically wiped away, leaving room for not more than one large ophite flow, which might be the one which occurs at and above the top of No. I and at the bottom of No. V. Since No. V and No. I are 2092 feet apart, at right angles to the strike, and No. V is 108 feet the lower, the top of No. I, with dip = 13° , would correspond to $(483-108) 375$ feet, or with dip = 14° , to $(523-108) 415$ feet, in No. V, and the two holes would barely overlap. This is probable, as the bottom of No. V and the top of No. I are very similar; so that if not exactly the same horizon, they are probably from the same flow. If we can consider them identical, we can also assume that the top of No. I makes a continuous record with No. IV. (No. IV, 606 feet = No. I, 0 feet.) This seems on the whole the best plan, as drill hole No. V crosses and recrosses a fissure and there is no guarantee that the different parts of it are in any fixed relation to each other. But at the same time we must remember that in thus allowing about 270 feet of upthrow,* we may be shortening our column too much, but we may be reasonably confident that the beds we may have thus omitted are two or three large flows of ophite. There are certain reasons which make a fault of the nature we have described probable. We have already spoken (p. 78) of the probability that No. IV is thrown up, and the line of strike of the fault may be marked by the Washington harbor depression. (See also p. 60.)

* $3385 \text{ feet} \times 0.25$ (tan 14° , about the dip which Stockly determined in this locality) = 846 feet. From this subtract difference of level of corresponding points, 606 feet, less difference in altitude, $194 - 163.7$ or 30 feet, = 576 feet. $846 - 576 = 270$.

DRILL HOLE NO. V.

We give the record of No. V, though it will not be included in our general column.

- 0-104; (Ss. 15197-203). **Melaphyre**, ophite; veined, decomposed and laumonitic; at 18 feet about 2 feet of brecciated vein matter, with white and chloritic seams in the neighboring rock.
 105; (S. 15205). "Slide" rock, fine grained.
 130. A similar belt.
 150-152. Thoroughly decomposed; vein.
 188. A thin *fissure*; a red, calcareous, decomposed belt, very prehnitic; probably also a contact of flows.
 105-188; (Ss. 15205-10). **Melaphyre**, ophite; coarsest near 163 feet.
 188-210; (Ss. 15210-3). **Melaphyre**, ophite; first five feet amygdaloidal; feldspathic; mottling not prominent.
 210. **Clay** seam.
 231. Finer grained.
 210-343; (Ss. 15214-9). **Melaphyre**, ophite. Feldspathic, mottling not prominent, but rather a diabasic texture of feldspar laths; occasional amygdules, seams and veins; toward the bottom the mottling becomes more marked.
 343. Enter *fissure*; rock much decomposed, fine grained and prehnitic.
 344. **Clay** seam.
 346; (S. 15220). **Amygdaloid**, not far from contact; feldspathic.
 365. Leave fissure, i. e., the amygdaloidal zone.
 344-376. Perhaps one small **Melaphyre**, ophite.
 375. Cross fissure (?).
 376-415. **Melaphyre**, ophite; amygdaloidal at top.
 397. Cross fissure again (?). End of drill hole No. V.

DRILL HOLE NO. I.

Hereafter, in reducing from vertical depth along drill hole to thickness, 1-30 is taken off.

No. I, 0 feet, taken as equivalent to No. IV, 606 feet.

This corresponds very nearly to a dip of $14^\circ 20'$, which is what we have by correlation of No. I and No. III, p. 84.

- 0-63; (Ss. 15001-4). **Melaphyre**, ophite; mottled feldspathic and slightly amygdaloidal.
 63-153; (Ss. 15005-10). **Melaphyre**, ophite; amygdaloidal at top; darker, black, and mottled at bottom. *Copper* and prehnite seam, and spangles of *copper* on chloritic joints.

- 74 153-227: (Ss. 15011-6). **Melaphyre**, ophite; amygdaloidal the
(72) first 10 feet, which character fades out in the next 9 feet;
chlorite and calcite amygdules and veins.
- 48 227-275: (Ss. 15017-20). **Melaphyre**, ophite; 5 feet of amygdaloid
(46) at top, with a little *copper*.
- 23 275-298: (Ss. 15021-5). **Melaphyre**; fine grained, somewhat
(22) ophitic, amygdaloidal for 4 feet at top and 3 feet at bottom;
with prehnite, calcite and laumonite.
- 64 298-362: (Ss. 15026-37). **Melaphyre**, ophite; amygdaloidal for
(62) about 10 feet at the top, with chlorite and a little *copper*; at 316
feet vein of datolite (?) and *copper*; and at 321 feet *copper* again.
It is equivalent to the flow, from the top of No. III down to
44 feet, which is also a veined ophite with a seam containing
copper, at 19 feet.
- At the very bottom of the bed are some tubular amygdules
running lengthwise of the drill cores, i. e., perpendicular to
the contact, which contain some calcite, chlorite and *copper*.
- 15 362-377: (Ss. 15038-9). **Melaphyre**, amygdaloidal. Equivalent
in drill hole No. III to 44-59 feet.
- 9 377-386: (Ss. 15040-1). **Melaphyre**, amygdaloidal. Equivalent
in drill hole No. III to 59-67 feet.
- 39 386-426: (Ss. 15041-5). Fine grained amygdaloids and scoria-
(38) ceous beds with basic sediment mixed and at the bottom.
This is equivalent to the beds No. III, 67-110 feet, but the trap
and sediment being both fine grained, it is difficult to separate
them. We may be sure of having quite a marked scoriaceous
conglomerate here. There is a noteworthy amount of the
felsitic debris, the first such occurrence under the Allouez
conglomerate, No. VI, 363 feet, and there are also agate
pebbles.
- I take this to be the Kearsarge conglomerate, for reasons mentioned
below in connection with the Minong porphyrite.
- 30 426-456: (Ss. 15045-50). Minong **Porphyrite**; equivalent to No.
(29) III, 100-134 feet. This is quite acid, probably not belonging to
(4,097) the melaphyres at all, but rather a felsite porphyrite. No
olivine can be recognized in it with certainty, either microscop-
ically or otherwise. The character is more distinct under the
microscope, but the extreme fineness of grain, the scoriaceous
porous and brecciated appearance, peculiar in that the pores
are fine and irregular, can be recognized. We shall call this
the Minong porphyrite. Elsewhere it appears to be distinctly
a felsite porphyrite, but the unaided eye could hardly dis-
tinguish it as such in the drill cores. Now we find under the
lowest conglomerate in the Central mine, which Hubbard has
correlated with the Kearsarge (Proc. L. S. M. I., Vol. III,
1895, p. 75) a trap which appears to be of similarly acid

character, and I know of none such higher in the series, either
on Isle Royale or in the Central mine, that is below the
Allouez conglomerate. Now as to relative position, the Kear-
sarge conglomerate varies from 2,599 feet below the Allouez
at the Central mine to 2,239 feet at Calumet. According to
our reckoning, on Isle Royale it is (4,068-2,332 feet) 1,736 feet.
This is not far from two-thirds the thickness of the interven-
ing beds at the Central mine, and we may remember that on
page 68 we found the ratio of the distances between Marvine's
No. 43 and No. 65 to be $\frac{3}{4}$, very much the same. As to its
relations with other conglomerates, the distance between the
Kearsarge conglomerate, Marvine's No. 11, and the Allouez
conglomerate, his No. 15, is about cut in two by the Calumet
conglomerate, No. 13, and we have at 3,197 feet (i. e., No. IV,
133 feet) a basic sandstone, which may represent it, or this
may be the North Star conglomerate, No. 12, and the Calumet
conglomerate may be represented by the sediment 24 feet
higher in the series. At any rate the period of slackened
eruptive activity in that portion of the series is marked.

Then nearer the Allouez conglomerate than the Calumet is the
Houghton conglomerate, No. 14, and of that we find traces at
2,532 feet. These two intermediate beds, the Calumet and the
Houghton conglomerates, are much thinner and more basic in
character than along Keweenaw Point,* but that is what we
should expect from the general thinning out of all the rocks.
The correlation is then fairly satisfactory, and the more so,
because in constructing our column (p. 80) we have, between
drill holes No. IV and No. I, allowed for 270 feet of faulting,
of which we were by no means sure. That our correlations
come out thus well, strengthens us in our confidence that we
were right in allowing for that fault.

- 80 456-536: (Ss. 15051-5). **Melaphyre**, porphyrite, the "Minong
(77) trap;" equivalent to No. III, 135-415 feet. It is sometimes
faintly mottled toward the lower third of its thickness, but in
general it is much finer grained for its size than the ophites.
It is compact and has a clean conchoidal fracture, and tends to
basaltic jointing. Occasional fair-sized carnelian agates are a
feature of this bed. On the other hand it differs from the
porphyrites above the Greenstone aside from microscopic
characters by being much darker—black, rather than grayish
green. It can be traced almost continuously the full length of
the island, from a projecting point on the north line of Sec.
35, T. 64, R. 39, through the Wendigo property, where the
trail running from Sec. 20 to Sec. 15 (Pl. III) is nearly

* See later part of this volume, where the Houghton conglomerate in the Peninsula
mine is shown to be very basic in its lower half.

along its outcrop. Its lower contact was opened up by numerous costeans on the northwest side and by tunnel No. 5. It runs along the south side of Todd Harbor, where it was again developed by costeans (I and II), and at McCulloch's mine (p. 5). Passing near the west quarter post of Sec. 27, T. 66, R. 35, it formed the foot of the more extensive workings of the Minong mine (though there was also some test-pitting under it), and thence may be followed to the north side of Locke Point.

At the bottom of this flow we pass from the record of drill hole No. I to that of No. III. No. I, 536 feet, is No. III, 215 feet, i. e., 321 feet higher. Adding the excess of elevation of No. III over No. I ($231 - 164 = 67$ feet), we have 388 feet difference in level, which divided by 1,518 feet, the distance between the two holes in the direction of the cross-section, gives a dip of $14^{\circ} 20'$. This is the most accurately determined dip that we have, and we get the same result by supposing that the bottom of No. V just laps the top of No. I, and we shall also get the same result by correlating No. III and No. XIII. Stockly's observations, using the outcrop at the surface near tunnel No. 5, made the dip a little less ($14\frac{1}{2}^{\circ}$), but only a fraction of a degree. There is no indication of a fault either way between No. I and No. III, and there is no possibility of much of a fault.

(4,174)

DRILL HOLE NO. III.

94	215-309; (Ss. 15123-8). Melaphyre , ophite; equivalent to No. I,
(91)	536-630 feet (Ss. 15056-61); quite amygdaloidal at top, with traces of a sedimentary parting.
0	309; (S. 15129). Sediment, i. e., Shale ; mainly composed of plagioclase feldspar, but there is some quartz in it; cf. No. I, 630 feet; may perhaps be two or three feet thick.
(4,265)	309-339; (Ss. 15130-3). Melaphyre , amygdaloidal. Veined and seamed; very feldspathic; corresponds to No. I, 630-662 feet. (S. 15064).
30	339-363; (S. 15134). Melaphyre , amygdaloidal; drill hole No. I extends down to 700 feet, but is much decomposed in the lowest part, and the beds there are not easily separable.
(23)	363-410; (Ss. 15135-8). Ophite , amygdaloidal; possibly two flows, separated at 380 feet.
47	410-453; (Ss. 15139-42). Melaphyre , ophite.
(45)	453-473; (Ss. 15143-4). Melaphyre , feldspathic.
43	
(42)	
20	
(19)	

89
(86)
(4,509)

473-562; (Ss. 15145-51). **Melaphyre**, ophite; at 497 feet the drillers are said to have struck a vein and to have followed it for 82 feet. S. 15149 at 496 feet and S. 15150 at 545 feet show a prehnite and calcite vein with crystallized *copper*.

DRILL HOLE NO. XIII.

At this point it seems best to pass to drill hole No. XIII, whose beginning is in a band of very chloritic amygdaloid close to the north of some bluffs of ophite. Two holes were put down here, one vertical and the other, No. XIII A, at an angle of 45° to the east. Drill hole No. XIII is somewhat farther from tunnel No. 5, which is in the foot of the Minong trap (drill hole No. I, 536 feet = No. III, 215 feet), than the tunnel is from drill hole No. I. The distance from No. III to No. XIII is 1775 feet and the top of No. III is (231-216) 15 feet the lower. Hence, allowing the dip slope to be 1:4 ($\tan 14\frac{1}{2}^{\circ}$) the top of No. XIII, in the absence of faults, would correspond to No. III, 459 feet. The first samples of the vertical hole No. XIII were accidentally mixed from 31 feet to 113 feet, so that we shall have to use the record of No. XIII A for this part of our section. In hole No. XIII the rock grows less amygdaloidal after the first 17 feet and in hole No. XIII A after the first 35 feet (v. 25),* then the hole passes into a uniform looking gray ophite which begins to be finer grained about 79 feet (v. 56 feet), but we do not reach its bottom, for at 86 feet (v. 61 feet), we cross a fissure, then, at 132 feet (v. 93 feet), come to a marked contact of two quite amygdaloidal flows, with *copper* and prehnite in the amygdules. From this point the rock is once more a massive ophite down to 208 feet (v. 147 feet), where there is another contact, with a band of basic sandstone. In No. XIII we have no distinct record until after 113 feet; then we meet a contact with a little sandstone at 125 feet. After this the rock is coarse grained down to 166 feet, when it becomes finer and grows amygdaloidal with vertical clay seams, down to 240 feet. At 230 feet we find a foot of sandstone like that at 125 feet. There are petrographic reasons, in the nature of the feldspar in the adjoining flows, for thinking that No. XIII A (v. 93 feet) corresponds to No. XIII, 125 feet. If we suppose, as indicated by the dip, that the amygdaloid at the top of No. XIII is that which occurs in No. III, 453 feet, then the first 17 to 25 feet of amygdaloidal rock will correspond to a point in No. III, down about 473 feet. Then for the bottom

* The numbers referring to XIII A with a v. before them are the distances reduced to the vertical by multiplying by $\sin. 45^{\circ}$, i. e., 0.7071.

contact of the big ophite next below, at No. III, 562 feet, our first match will be No. XIII, 125 feet, and No. XIII A (v. 93 feet). If we compute the dips from these correlations, we find that we have 562-125 + difference in altitude (216-231) is 422, divided by distance at right angles to strike, from No. XIII to No. III, 1,775 feet, is 0.238, or $\tan 13^\circ 20'$; 562-93 + difference in altitude (216-231) is 454, divided by distance at right angles to strike, from No. XIII to No. III, 1,775 feet, is 0.256, or $\tan 14^\circ 20'$.

It is not likely that the dip is becoming flatter as we go northwest from this point, for in general it grows steeper in that direction, and the dip about No. III was determined (p. 84) with the aid of No. 5 tunnel, as $14^\circ 15'$. It is therefore probable that the lower part of No. XIII A is more nearly in undisturbed relations with No. III, 562 feet, than is No. XIII, though the dip may be steeper than thus indicated. Then the fault which cuts No. XIII A at 86 feet must separate No. III, 562 feet, from No. XIII, 125 feet. It has an upthrow of (125-93) 32 feet, and in that case the amygdaloid at the top of No. XIII should correspond to No. III, 437 feet, but this is not a good correlation at all. The correlation found by assuming that the ground between the top of No. XIII and No. III is undisturbed, i. e., that $(1775 \times 0.256 = 454 + 15)$ No. XIII, 0 feet, is equivalent to No. III, 468 feet, is much better. If we accept this correlation, we must imagine that the fissure vein which crossed No. XIII A crosses No. III also, probably being the vein entering at No. III, 497 feet, and throwing the part above up. Now drill holes Nos. XII, XIV, XIII, tunnel No. 5 and drill holes Nos. III and I, were all located near a supposed fault or vein which is indicated by a topographic break that runs a little east of north. A vein in about this position was indicated on Hill's map, 1871. Now such a fault, if a normal fault with a hade slightly to the west, is just the one to have done the work we have attributed to it, passing a little to the east of No. XIII and No. III, but cutting into No. III at 497 feet. Figure 11 illustrates it, looking in the direction of the strike of the rocks. Now, there is a fissure that comes into No. XIII at about 252 feet or a little higher, and it will be interesting to compute what the dip of the fault would be if the latter were a continuation of the former. Of course, too much stress should not be laid on this computation, because fissures are irregular, and because inclined drill holes are very liable to go astray. But supposing that all is right, we find (Fig. 11) the following results:

Using a projection plane this time in the direction of the strike, that is, imagine we are looking northwest. From A draw AD,

representing hole No. XIII, and at 45° AB, representing hole No. XIII A. Let B be the point where the fault cuts hole No. XIII A (86 feet), and C a point at the same level in No. XIII ($86 \times \tan 45^\circ$, i. e., 61 feet). CB is also 61 feet. Let D be the point where the fault is supposed to cut No. XIII (252 feet). Then CD is 191 feet and the $\tan \angle CDB$ is CB/CD , i. e., $\frac{61}{191}$. Now in the stereographic projection around C the direction of dip of beds is foreshortened to C, and the strike of the fault foreshortened to CN. If we draw CF from C parallel to BD, CFN will represent the fault. The dip of the fault will be $\angle CNF$. CN will represent the difference between the direction of dip of the beds and the direction of strike of the faults, say 35° , and $\angle FCN$ is 90° plus $\angle FCD$, which latter is equal to the angle $\angle CDB$. Finally CF is 90° , so that we have only to deal with right spherical triangles, and we have the simple formula—

$$\tan \angle CNF \text{ (the dip of fault)} = \tan NCF \times \sec CN$$

$$= \frac{1.22}{\tan \angle CDB, \text{ i. e., } \frac{61}{191}}.$$

which gives us $\tan \text{dip} = 3.8$, i. e., dip of fault is 75° .

A dip of 75° , which brings the fault nearly perpendicular to the bedding, is not beyond the range of probability. It is then quite likely that this fault has cut 31 feet out of the thickness of the ophite No. III, 473-562, and a corresponding amount out of No. III near No. XIII, 252 feet. Following our general rule, however, that we shall make the series as short as possible, we shall make no additions for this in our geological column.

The record of drill hole No. XIII is then as follows:

DRILL HOLE NO. XIII.

(4,509)
1
58
(56)
45
(43)
1

125-126; (S. 15722). **Sandstone**, basic and red.

126-184; (Ss. 15723-41). **Melaphyre**, ophite.

184-229; (Ss. 15742-5). **Melaphyre**, feldspathic ophite.

229-230; (S. 15746). **Sandstone**, basic, associated with clay veins running into hanging and foot. This or the bed at 125 feet may represent Marvine's slaty sandstone, No. 9; at least either of them is in about the right position for it, if the Minong conglomerate is the same as the Kearsarge conglomerate—4509 respectively 4611, minus 4068 = 441 feet respectively 543 feet below. But this is only a suggestion.

- 22 230-252; (Ss. 15747-51). **Melaphyre**, amygdaloidal, fine grained;
 (21) red, with clay veins from the top and the bottom; brecciated
 and prehnitic. Seems to be of the porphyrite type.
 90 252-342; (Ss. 15752-61). **Melaphyre**, ophite; feldspathic.
 (87)
 7 342-349; (Ss. 15761-2). **Melaphyre**, amygdaloidal.
 10 349-359. (S. 15763). **Melaphyre**, amygdaloidal; prehnitic.
 (4,735)
 88.5 359-447.5; (Ss. 15764-72). **Melaphyre**, ophite; amygdaloidal for
 (86) the first 8 or 9 feet.

447.5-503; (Ss. 15773-9). **Melaphyre**, porphyrite; has a peculiar character microscopically, which we find again in the bed at the top of No. XIV; red; fine grained; laumonitic, with chlorite and calcite; very feldspathic, with little augite visible, even under the microscope.

With this bed we pass to the record of drill hole No. XIV. If we compute where, in No. XIII, the top bed of No. XIV would be, with the dip that we have hitherto used, we find that it would correspond to No. XIII, 406 feet (distance along dip 1,518 feet $\times \tan 14^\circ 20'$, i. e. $0.256 = 388$ feet, to which add difference of altitude of No. XIV and No. XIII, 216-198 feet, = 18 feet, making in all 406 feet), right in the middle of a big ophite, whereas as a matter of fact the top of No. XIV lies under and to the north of an ophite bluff, and begins in beds like those at the bottom of No. XIII, as already stated. There is therefore little doubt that the top of No. XIV corresponds to beds near the bottom of No. XIII, while the exact correlation is uncertain, the range being between No. XIII, 503 feet, No. XIV, 11 feet, and No. XIII, 448 feet, No. XIV, 11 feet, the correlation may possibly be No. XIII, 493 feet, to No. XIV, 22 feet, an intermediate and otherwise most plausible correlation. Then we shall have (471 feet — 18 feet) 453 feet for the difference in level of corresponding beds or (453 divided by 1518 = 0.300) a dip of $16^\circ 40'$ here. If this steeper dip were due to a fault, it would mean that No. XIV was on the up-throw side, and the bottom of No. XIII on the down-throw side, but there is no reason to think that there is any fault and every reason to believe that this is the true dip, normally increasing. Consequently for No. XIV we use the factor 0.0438, to reduce from vertical width along hole to true thickness.

For the next flow we have, from No. XIII, 447.5 to 493 feet, already given, 45.5 feet, lapping over on the first 22 feet of No. XIV.

45.5
 (44)
 (4,865)

DRILL HOLE NO. XIV.

- 116 22-138; (Ss. 15780-9). **Melaphyre**, porphyrite; the last 10 feet of
 (111) No. XIII are equivalent to this; at 30-33 feet a seam of
 prehnite with numerous *copper* crystals; at 90 feet and again
 at 123 feet a chloritic seam with *copper* and calcite.
 61 139-200; (Ss. 15790-7). **Melaphyre**, ophite; feldspathic, first 9
 (58) feet amygdaloidal; toward the bottom, veins with prehnite
 and *copper*.
 2 200-202; (S. 15798). **Sandstone**, basic; with amygdaloidal frag-
 ments. This is hardly in the right place for Marvine's
 conglomerate No. 8, though we are coming near to its position.
 165 202-367; (Ss. 15799-810). **Melaphyre**, ophite; amygdaloidal the
 (159) first 9 feet; seamed near 299 feet; a typical coarse ophite which
 helps to form the northwest front of the island.
 69 367-436; (Ss. 15811-8). The Huginnin porphyrite. This very
 (67) marked and peculiar bed has a fine grained red ground-
 mass, in which are large crystals of whitish feldspar, fre-
 quently about a fifth to a half of an inch long. It is not
 uniformly amygdaloidal, but has streaks of half-filled vesicles
 with chlorite and *copper* and prehnite and *copper* veins. It has
 distinct lines of flow and the upper 10 feet may be an inde-
 pendent flow. The prehnite and *copper* veins and laumonite
 seams occur throughout the bed to the bottom. This por-
 phyrite outcrops in the bed of Huginnin Creek about 50 feet
 from the shore of Huginnin Cove and about 200 feet from the
 mouth of the creek; whence its name. Lying, as it does,
 between two more resistant big sheets of ophite, and having a
 sediment under it, but little is seen of it in spite of its very
 peculiar and easily marked character. There is no flow like
 it in the whole series. We do, however, catch another glimpse
 of it near the mouth of McCargoe Cove, about 500 paces north
 and 1,300 paces west of the southeast corner of Sec. 13, T. 66,
 R. 35, where it occurs with a similar environment. It seems
 to have caught Foster and Whitney's eyes.
 4 436-440; (Ss. 15819-20). **Ash**, brecciated. The microscope shows
 (5,264) conchoidal glass forms in this rock.
 165 440-605; (Ss. 15821-34). **Melaphyre**, ophite. This big flow rivals
 (158) the "backbone" greenstone. It appears to have more iron
 than the latter. It is so much finer grained toward the bottom
 of the hole that we must infer that there are not more than
 10 feet more of it. This big ophite being beneath the por-
 phyrite at Huginnin Cove, will be expected to make the front
 range of the northwest coast. Now along this coast three

holes were put down, Nos. XII, XV and XVI. They are all about on the same line of strike, No. XV about 10 feet lower than No. XVI and No. XII about half-way between them in position. The samples from No. XII were thrown into confusion by fire, but we have a few that are well authenticated, from the bottom beds and from some other characteristic beds, and we have Stockly's record.

We find in the field that drill hole No. XV lies on the east or upthrown side of the fault already mentioned, No. XVI on the west; No. XII lies very near the break, but apparently also to the east of it. On comparing records, however, we find that No. XII is much more nearly in accord with No. XVI, at least in the lower part, indicating either that the fault is east of that part of No. XII or that the character of the upthrow has changed. Field observations above No. XV show a series of amygdaloids capped by an ophite under which we get a good contact, and a dip 18° to N. 26° W. This contact is about 87 feet above the lake, on a slope whose angle is 28° , while No. XV is only a little above the lake and close to it.

The following sketch (Fig. 12) shows the section at No. XV, and shows that the top of No. XV appears to be something over 100 feet lower than the big ophite at the bottom of No. XIV. Attacking the problem in another way, we find that if the dip remained $16^\circ 40'$, the beds at the lake shore ($1,300 \text{ feet} \times 0.300 = 390 \text{ feet}$ + the altitude of No. XIV, 198 feet) would correspond to No. XIV, 588 feet, which is right in the middle of the big ophite; they are evidently below it. Taking, however, a dip of 18° , a field observation which was on a very good exposure of the under contact of the big ophite aforesaid (Fig. 12), we find ($1,300 \times 0.325 + 198 \text{ feet}$) that the beds at the lake shore would correspond to No. XIV, 620 feet, which would thus bring the drill holes, if not displaced by faulting, directly beneath the ophite. This is the position occupied by No. XVI, which according to the testimony of the conglomerates that we meet in it begins about 50 feet or more higher up in the series than No. XV. If, therefore, we suppose that the record of No. XVI begins where that of No. XIV leaves off, we shall be in harmony with the observed dips, and not be in danger of leaving out more than some (100 feet — 50 feet) 50 feet of amygdaloids such as are exposed above the mouth of No. XV. It should be said, however, that the nearer the top we compare No. XV and No. XVI the less faulting there seems to be between them. But the records of their upper parts are not very clear, and I fear the samples were not carefully arranged in the boxes.

There is another difficulty and uncertainty attending the construction of this end of our column. We have seen that the dip seems to be increasing faster and faster. Now we have no outcrops nor drill holes farther to the north to guide us as to the rate at which this increase progresses as we go down or to the north, and consequently the amount of allowance for reduction from vertical width to thickness is much more uncertain. We have to guide us a number of dips measured on drill cores which, as we have seen, are not very safe guides, and also we have the dips as exposed on Amygdaloid Island, and on adjacent islands, toward the other end of Isle Royale, which correspond to these lower beds. Both these dips and the dips on the drill cores agree in indicating an increase over the dips observed higher in the series, i. e., toward the south-east. In such case the allowance for dip, and the dip assumed, are matters of general judgment rather than of precise calculation. I have recorded the dips observed on the drill cores. We will continue to assume the 18° dip down to the first conglomerate at No. XVI, 437 feet, which involves taking off 1-20 to reduce from vertical width to thickness.

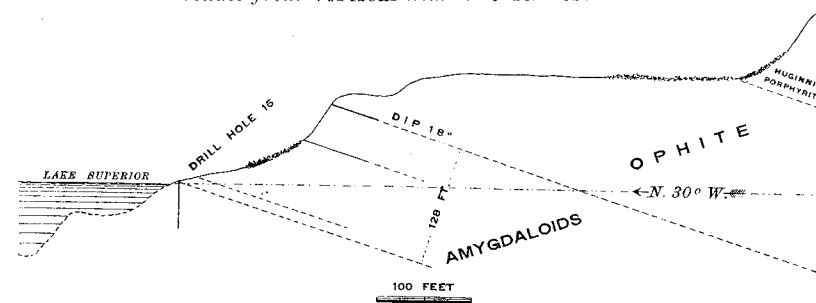


Fig. 12

Cross-section near drill hole No. XV.

We will base our description here on the record of No. XVI, as it is the deepest hole from which we have a full set of cores, and then give Stockly's record of No. XII and a summary of that of No. XV.

DRILL HOLE NO. XVI.

- | | |
|------|--|
| 39 | 0-39; (Ss. 15835-7). Melaphyre , ophite; chloritic amygdules at |
| (38) | top of bed. |
| 15 | 39-54; (Ss. 15838-40). Melaphyre ; streak of green prehnitic |
| (14) | amygdaloid at top. |

- 27 54-81; (Ss. 15840-2). **Melaphyre**; red and amygdaloidal for the
 (26) first 6 to 8 feet, with calcite and laumonite (?) in amygdules.
 33 81-114; (Ss. 15843-7). **Melaphyre**, amygdaloidal; at the top the
 (31) bed is a green prehnitic amygdaloid like that at 39 feet, which
 I suppose to crop out under the lake. From 88-99 feet it is
 5,532 much broken and shattered and appears amygdaloidal.
 40 114-153.5; (Ss. 15848-50). **Melaphyre**, feldspathic; intermediate
 (38) between porphyrite and ophite.
 11 153.5-165; (Ss. 15851-3). **Melaphyre**, amygdaloidal; at the top
 (11) there is a green decomposed seam; laumonitic amygdules.
 9 165-174; (Ss. 15854-5). **Melaphyre**, amygdaloidal.
 12 174-186; (S. 15856). **Amygdaloid**.
 (11) 186-201; (Ss. 15857-8). **Melaphyre**, amygdaloidal; at 201 feet
 15 there is a decomposed green seam, which may be a vein or a
 (14) decomposed margin between two flows.
 25 201-226; (Ss. 15859-62). **Melaphyre**, amygdaloidal. All the
 (24) above series of amygdaloidal melaphyres are small flows of
 the ophite type.
 32 226-258; (Ss. 15863-7). **Melaphyre**, feldspathic.
 (30) 258-275; (S. 15868). **Melaphyre**.
 17 275-297; (Ss. 15869-71). **Melaphyre**, amygdaloidal.
 (16) 297-320; (Ss. 15872-3). **Melaphyre**, ophite; amygdaloidal.
 22 320-348; (Ss. 15874-7). **Melaphyre**, ophite; vesicular and amygdaloidal, with laumonite, for the first 13 feet.
 (21) 348-391; (Ss. 15878-82). **Melaphyre**, ophite.
 23 391-410; (Ss. 15882-4). **Melaphyre**, amygdaloidal.
 (22) 410-438; (Ss. 15885-7). **Melaphyre**, ophite.
 28 438-447; (Ss. 15888-96). **Breccia or Scoriaceous Conglomerate**;
 (41) a mixture of fine grained sandstone and of a porphyrite like
 19 the Huginnin porphyrite.
 (18) *From this point we shall take off 0.06 to reduce from vertical width*
 (27) *to thickness, implying a dip of about 20°.*
 10 455-475; (Ss. 15897-8). **Porphyrite**; like the Huginnin porphyrite. No. XIV, 367-436 feet.
 5,849
 20
 (19) 5,868
 12
 (11) 475-487; (Ss. 15899-906). **Conglomerate**, red, with numerous
 cavities, and much basic debris, but also with a great deal of
 quartz porphyry which is sometimes spherulitic; cement
 largely calcareous. This conglomerate which occurs in No.
 XII from 471 feet to 493 feet, and in No. XV from 429 feet to
 444 feet, being the first bed that can be identified with absolute
 certainty in all the holes, is said by Stockly to contain copper

in No. XII (p. 95). This is natural, as drill hole No. XII seems, as we have said, to lie nearer the fault. This conglomerate would seem to be thickening toward the northeast, and while occurring at practically the same level in both No. XII and No. XVI, is 40 to 50 feet higher in No. XV, as already remarked, thus indicating the fault already studied (p. 90). This is really the first well-marked conglomerate with porphyry pebbles that we have met below the Allouez conglomerate, No. VI, 363-386 feet. It is about (5879-2332) 3547 feet below the latter, and in the remainder of the record we find four considerable conglomerates and at the bottom a porphyry. Now we see in Marvine's table of conglomerates facing p. 60,* that after a considerable gap devoid of conglomerates, we have a group, Nos. 8-4, opposite or east of the Isle Royale mine, and Nos. 6-4, opposite or east of the Kearsarge mine, about 6529 feet below the Allouez conglomerate. Now the ratio 3547:6529 is not far from the similar ratios already found (p. 83), 1736:2599 and (p. 68) 396:573. On Keweenaw Point, moreover, at the extreme bottom of our series, we find a porphyry—not only the quartz porphyry, 200 N. 600 W., Sec. 36, T. 56, R. 33, mentioned by Irving (pp. 104, 196; cf. Marvine p. 60), but also (in part more like the one at the bottom of No. XVI) one from the Suffolk mine at Praysville, 50 paces N., 1,825 paces W., Sec. 10, T. 57, R. 31 (Irving, p. 177); and 50 paces N., 1,450 paces W., Sec. 4, T. 56, R. 32; and 550 paces N., 1,400 paces W., Sec. 30, T. 56, R. 32; also at the Douglass Houghton ravine (U. S. G. S. Bull. No. 23, p. 43) on Sec. 36, T. 56, R. 33, near the east quarter post. Thus porphyries are evidently quite persistent in connection with a lower group of conglomerates, and we may also mention the porphyries found around Bare Hill and Mt. Houghton, which are much more like the Isle Royale occurrence in question. We have no marked change in the character of the lavas at this point as we have above the Greenstone, by which we can make an exact and certain identification, but we may with much certainty say that we have arrived at the top of the lower group of felsitic conglomerates, and as Marvine's No. 6 is the first one which he makes continuous, we will provisionally correlate this Isle Royale bed with it, for thus we best express its position at the top of a group of four closely following conglomerates. Of course the scoriaceous bed at 438 feet might be taken as Marvine's No. 6, in which case this conglomerate (475 feet) would be his No. 5, but the bed at 438 feet is not felsitic.

* Geol. Sur. Mich., I, Pt. II.

- 124
(117)
(5,996)
7
(6,003)
- 46
(42)
33
(30)
- 89
(80)
(6,155)
124
(112)
- 90+
(80)
- 487-611; (Ss. 15906-18). **Melaphyre**, ophite: amygdaloidal at the top; has much more magnetite than, for example, the "backbone" greenstone. Cf. Pumpelly. Geol. Sur. Mich., I, Pt. II, p. 17.
- 611-618; (Ss. 15919-23). **Conglomerate**; with basic and acid pebbles: dips observed, 21°, 26°, 27°.
- Hereafter 1-10 will be taken off to reduce from vertical width to thickness, corresponding to dip of 26°.*
- 618-663.5; (Ss. 15924-8). **Porphyrite**.
- 663.5-697; (Ss. 15929-38). **Conglomerate**, scoriaceous; like 438-445 feet in its character and in its pebbles. It is not at all unlikely that similar conglomerates, which are a brecciated mixture of sandstone and trap, represent real though perhaps slight erosion unconformities, the underlying bed having been eroded. Dips 28°, 29°.
- 697-786; (Ss. 15939-45). **Melaphyre**, ophite; the bottom five feet are a fine grained brecciated black trap, the dip of the lines of amygdules being 27°.
- 786-910; (Ss. 15946-85). **Sandstone**, passing into **Conglomerate** and **Porphyry Tufa**. Dips: at 796 feet, 52°; at 803 feet, 50°; at 808 feet, in a sandstone streak, 63°; at 817 feet, 40°; at 830 feet, with signs of unconformity and cross-bedding, 35°; at 850 feet, 37°. This bed is very largely of fragments such as the underlying rock might furnish, and largely in the concave forms of ash or glass fragments, which do not imply an erosion of the source, but at the top of the bed there is sediment proper, some of which may have been derived from other rocks than the underlying felsite. At the bottom of this conglomerate the passage into felsite is so gradual that I at first fixed the dividing line at 924 feet, and I think the conglomerate may be considered practically contemporaneous, that is immediately subsequent to the felsite, even though the former derives some of its material from the latter. Chalcedonic dots are characteristic of the whole formation (Rosenbusch, Vol. I, ii, i) and a bluish fluorite, first noticed under the microscope, was visible also to the unaided eye. The tufa is sometimes dark, but often light, often greenish, with sandstone boulders, or brecciated with angular green spots.
- 910-1000+; (Ss. 15986-98). **Felsite**, very fine grained; a typical felsite; porphyritic crystals, extremely small and rare; quartz not certainly visible. This, with the Minong felsite porphyrite may seem to meet Irving's anticipation (*loc. cit.*, p. 331) of red acid rocks on the north side of the island. We have already called attention to the felsites that occur at various points far down in the series on Keweenaw Point. But

by far the closest lithological resemblance of this bed is to the felsites of Bare Hill, Sec. 29, T. 58, R. 28, and to those that occur near the mouth of the Little Montreal River on Sec. 26, and Sec. 27, T. 58, R. 28, which are described elsewhere in this volume.

We add for completeness sake the record of hole No. XII from Mr. Stockly's notes, and of No. XV from samples gathered.

DRILL HOLE NO. XII.

- 13-79; **Trap**, gray.
- 79-107; **Amygdaloid**; sample from 107 feet?
- 107-168; **Trap**, amygdaloidal and chloritic; samples from 102, 160 and 165 feet.
- 168-174; **Amygdaloid**.
- 174-176; **Trap**; sample from 175 feet.
- 176-183; **Amygdaloid**.
- 183-228; **Trap**, slightly amygdaloidal near middle of belt; sample from 217 feet.
- 228-243; **Amygdaloid**; secondary minerals scanty; samples from 231 and 237 feet.
- 243-249; **Trap**.
- 249-264; **Amygdaloid**; secondary minerals very scanty; sample from 251 feet.
- 264-270; **Trap**.
- 270-276; **Amygdaloid**, with a little *copper*.
- 276-290; **Trap**, fine grained, black.
- 290-292; **Amygdaloid**, chocolate colored.
- 292-341; **Trap**, slightly amygdaloidal.
- 341-344; **Amygdaloid**, blended with underlying trap.
- 344-383; **Trap**, amygdaloidal near top.
- 383-398; **Amygdaloid**.
- 398-440; **Trap**.
- 440-457; **Amygdaloid**.
- 457-464; **Trap**.
- 464-471; **Amygdaloid**, poorly defined.
- 471-493; **Conglomerate**, with *copper*.
- 493-510; **Amygdaloid**.
- 510-602; **Trap**.
- 602-610; **Conglomerate**, with a fine sandstone near foot. Specimen from this bed probably?
- 610-616; **Amygdaloid**, well mineralized.
- 616-656; **Trap**, amygdaloidal near hanging and crumbly near foot wall.
- 656-664; **Sandstone**, mixed with amygdaloid near foot. Specimen from this bed probably.

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664-683; **Trap**, slightly amygdaloidal.

683-796; **Trap**, fine grained, black.

796-807; **Amygdaloid**.

807-819; **Conglomerate**, made from broken amygdaloid.

819-843; **Amygdaloid**; specimen from 843 feet.

843-1054; specimen from the bottom showed that the drill was still in the felsite. This adds some fifty feet to the section given.

(53)

6,400

DRILL HOLE NO. XV.

(Thin sections have not been made.)

0-24; **Amygdaloid**.

24-44; **Trap**; amygdaloidal for the first 11 feet.

44-64; **Trap**, with 6 feet of amygdaloid at top.

61-79; **Amygdaloid**, with green streak at top like No. XVI, 31 feet, 89 feet and 154 feet.

79-115; **Melaphyre**, ophite; amygdaloidal for first 15 feet and occasionally (pseudamygdaloidal) down to 98 feet, then lustre mottled and growing redder and finer grained.

115-124; **Amygdaloid**; green seam for the top 2 feet, then a marked laumonitic amygdaloid.

124-130; **Amygdaloid**.

130-135.5; **Amygdaloid**.

135.5-147; **Amygdaloid**; at 144 feet a *copper* and prehnite vein.

147-159; **Amygdaloid**; green seam at upper contact; lower contact brecciated.

159-164; **Amygdaloid**; green seam at top.

164-192; **Melaphyre**, ophite.

192-216; **Amygdaloid**; green seam at top with red veins at bottom.

206?-222?; **Amygdaloid**.

222-256; **Amygdaloid**.

256-265; **Amygdaloid**.

265-285; **Amygdaloid**.

285-294; **Amygdaloid**.

294-297; **Amygdaloid**?

Zones of finer grain at—

297 feet.

298 feet.

300 feet.

302 feet.

313 feet; green and amygdaloidal.

318.5; **Amygdaloid**; fine grained, with prehnite and laumonite.

323; finer grained streak.

Drills—one and one-half inch core—were used.

	XI.	XII.	XIII.	XIV.	General averages.
92.	Mar 7, 1892.	Apr. 23, 1892.	Apr. 22, 1892.	May 27, 1892.	
92.	Apr. 6, 1892.		May 10, 1892.	June 25, 1892.	
	134	92	66	76	89.1
	144	88	65	76	85.3
	88	84	79	66	87.4
	85	114	67	89	105.6
	99	115	92	103	114.4
		121		102	138.1
		109			123.
		117			
		138			
		251			
	80	165	46		
				51	
	0.86	0.79	1.37	1.17	0.95
	550.5	1038	504	596	*8100.5

to engage in work which was not connected with the drilling. For the latter reason,

323-385; **Melaphyre**, ophite; green and crumbling at 324 feet, and at 332 feet much broken; thereafter more compact; at 383 feet and 384 feet, as well as 385 feet, fine grained streaks. It seems as if there were a slide hereabouts, as above this point the series cannot be matched with No. XVI, while below it the matches are very good.

385-395; **Trap**.

395-403; **Sediment**, like that at No. XVI, 438-447 feet.

403-429; Cf. No. XVI, 455-575 feet.

429-444; Cf. No. XVI, 475-487 feet; **Conglomerate**, very red.

Apparent dip 20°.

444-548; Cf. No. XVI, 487-611 feet; **Melaphyre**, ophite.

548-570; Cf. No. XVI, 611-618 feet; **Conglomerate**, not as red as above; much broken up; trap boulders (?) and breccia; dip 40°?

570-610; Cf. No. XVI, 618-663.5 feet; **Trap**, fine grained; nowhere very coarse.

610-626; Cf. No. XVI, 663.5-697 feet; **Sandstone**, passing downwards into a black breccia; dip 27°.

626-736? (Core box No. 23 was marked inside "715-736," outside "No. 25, 736- bottom"). **Melaphyre**, ophite, as in No. XVI.

We have been over the geological column in some detail, but before we leave it, it would be well to take one flying glance to see if there may not have been some repetition in the series on a grander scale than the mere overlapping of adjacent drill holes. If we can show that each hole has its peculiar character or contains some unique bed, i. e., one not elsewhere found in the series, we shall be sure that there is no mighty fault that has reduplicated the series on a large scale.

Beginning then once more at the south side of the island, drill hole No. XI is characterized by a large number of acid conglomerates, with small basic flows. No. X has the Island mine conglomerate, with all the peculiar relations and accompanying change in the character of the flows and conglomerates fully described on p. 61 *et seq.* It has also the first scoriaceous conglomerate, No. 44 of Marvin, from 415-426 feet. In drill hole No. IX we have a number of flows of a green acid type which give the hole a peculiar character, though similar things are found to some extent in the immediately adjacent holes. Their relations have already been fully discussed.

It has also the Ashbed series, p. 66. In No. VIII, beside the green porphyrite flows, there is a characteristic bed of chocolate sandstone, about 40 feet thick, with hardly any conglomerate, fully described on page 69.

In Nos. VII and VI we have the interesting and unique narrow band of felsite tufa, and, besides, in No. VI we have the Greenstone, the "backbone" and biggest ophite of all, with the bed at its base that we correlate as the Allouez conglomerate, p. 74. Nos. II, IV and V have no very marked character, though they are largely in heavy ophites, but we have stricken out of the column 276 feet there on the score of a fault. Nos. I and III have the very characteristic Minong group, porphyrite and trap. See p. 82. No. XIII is not so well defined, but No. XIV has the characteristic Huginnin porphyrite, p. 89, with its overlying and underlying large ophites.

The holes on the north shore of the island are quite characteristic, owing to the return of felsitic conglomerates once more and to the felsitic conglomerate and felsite at the base.

The table at the end of this chapter gives some of the principal beds, such as are used in the stratigraphic map, and also the probable correlations.

We have thus made sure that our column as given is a minimum, and that we have not overlooked any faults which would raise the south side, and make our section too long. But what can we say as to the other idea, that there may be faults which have let the southeast side down, and thus caused us unwittingly to leave gaps in our column, and not to make it as long as it should be?

Well, in many cases we have reasonably certain correlations, and in such cases no fault such as described could lead us astray. In the second place, such faults would cause us to find too steep dips from correlations, while in general the tendency is the other way—we find dips a trifle flatter than surface observations or than the observations in the drill cores would lead us to expect. In the third place, with a possible exception near drill hole No. IX, there are no south-eastward facing scarps or other indications of faults of that character.

Thus there is little probability that our column is much too short. It may be worth while in this connection to notice that the distance

between holes Nos. XI and XVI in a direction at right angles to the strike of the beds being about 23,518 feet, and the corresponding distance in our cross-section being 5,579 feet, the average dip between the two is $12^{\circ} 40'$, whose sine is 0.218. Thus if we had made the average dip $14^{\circ} 30'$ we should have made the thickness 5,880 feet, if 15° , 6,087 feet. If we had assumed a dip as high as $17^{\circ} 30'$ we should have obtained a thickness of 7,050 feet. Now if we had to depend on surface observations alone, we should probably have taken the dip as about 15° , and thus over-estimated the column some 500 feet.

§ 4. Isle Royale and Keweenaw Point cross-sections compared.

This seems to be an appropriate place also to compare our column with those given by Irving. We have preferred to make our detailed correlations with the cross-sections of our own reports, i. e., Marvin's, which Irving also used as the base of his work. And first, as to his notes on the Eagle River section (p. 170 *et seq.* Copper-Bearing Rocks, Mon. V, U. S. Geol. Survey), Irving assigns a greater thickness to the Great Conglomerate at the top of the section than we think appears on the island. The bed is, however, probably thicker on Keweenaw Point, as it is there much coarser. Then his next group (No. 6 of his map, Pl. XVII), is Marvin's group (c), coming down to our drill hole No. X, 426 feet, to which he assigned 1,417 feet as against 817 feet in our section. We, like Irving, divided this group into two parts at the Island mine conglomerate, finding in the lower group on Isle Royale an approximation to the character of the lavas in Irving's lower division.

The next group Irving limits at the bottom, we at the top, of the Ashbed. He follows Marvin's figures, but on his map he unites the next group, the Ashbed group, with this as No. 5. The next group, still following Marvin's figures, he brings down to the top of the Greenstone, corresponding practically to our division at drill hole No. VII, 91 feet, which makes 2,045 feet from the top of drill hole No. XI. We also divided this group rather arbitrarily, in order to trace the big sandstone at No. VIII, 419 feet. The peculiar felsitic bed that we find at the bottom of this group, i. e., just over the Greenstone, has not been seen on Keweenaw Point.* The next

* I at first wrote as above—afterward my attention was called to the occurrences noted at the end of this chapter. See also p. 72.

group, No. 4 of Irving's map, Marvine and Irving consider as one series made up of several beds, the basal bed forming the Greenstone ridge, while we recognize in the corresponding group on the island but two beds. Moreover, as previously stated, I have been over the ground carefully around the Phoenix mine, and am convinced that the alterations of "dark diorite" and "light diorite" are merely streaks of magmatic differentiation into more augitic and less augitic parts, the variation in the grain of the whole showing that the ridge and the group are mainly one great flow. The coarsest mottling observed in the samples in drill hole No. VI was about 7 to 9 mm., about 0.4 of an inch. This is in a flow 233 feet thick. Around the Phoenix mine the mottlings steadily increase in size, as we go north over the bluff, from four to the inch to scarcely one to the inch (25mm), and at the latter point we are so far up over the bluff, that supposing the grain to begin at once to diminish here (which it does not, so far as we can see), and supposing therefore that this point is up to the middle of the flow, the remaining upper part of the flow would take up so much of the space intervening between this point and No. 90 as to leave scant room for any additional beds. As Irving remarks, in all this distance there are no intercalated amygdaloidal bands, and though the mind may shrink from lava flows 1,200 feet thick, no valid reason can be given why they should not occur, especially in face of distinct indications that they do occur. As to the evidence from coarseness of grain, see Chapter V.

This brings us down to that great datum plane, the Allouez conglomerate, which we correlate with No. VI, 363-386 feet, 2,310 to 2,332 feet below the top of drill hole No. XI. From here we have some 685 feet of the Phoenix mine group, feldspathic ophites with no marked bottom to the group, and then Irving has to leave the accurately measured sections of Marvine and estimate a region of few exposures, little developed, except for an exposure of conglomerate 500 feet south of the center of Sec. 33, T. 58, R. 31, which is called the Kingston conglomerate, but may in all likelihood be the Kearsarge. (Cf. Cliff mine section.) Marvine and Irving take it to be 3,000 feet below the Allouez conglomerate, but the recent developments at the Central mine render probable that they over-

estimated the dip, and that it is really something less than 2,600 feet below the Allouez. This we have correlated with the Minong conglomerate, at No. I, 386 feet, 4,189 feet from the top of hole No. XI. The high ridges with coarsely lustre mottled ophites like the Greenstone, which occur in Sec. 4 and Sec. 9, T. 57, R. 31, may well correspond to the high ridges along the north side of the island with the big ophites exposed in drill holes No. XIII and XIV, and then we have Irving's No. 2 of his map, Pl. XVII, and the Praysville porphyry near the base of his group No. 1 to correspond to the bottom of our column. Irving has assumed for the dip from the Allouez conglomerate, or "slide," to the "Kingston" conglomerate, 30°. But if this latter is the Kearsarge and not a lower bed, the dip must be somewhat flatter. Then for the distance from this conglomerate to the Praysville porphyry he finds that the same dip would give 6,600 feet, to which to allow for a supposed increase in dip he adds 1,400 feet, making the total 8,000 feet, which would mean an average dip of 37° 20'. It is obvious that there is a chance for over-estimate here! Thus Irving (*loc. cit.* p. 177) gets a total thickness on Keweenaw Point of (15,190 + 2,200) 17,390 feet to our (6,555 feet + 2,600) 9,155 feet on Isle Royale, while within that part of the geological column where we can make close correlations, our Isle Royale section is about 2-3 of the thickness of the corresponding section on Keweenaw Point, which would in the same proportion be about 14,000 feet. It is probable that the greatest divergences are at the top and bottom of the section, and that our column may not represent a thousand feet or so at the top and that Irving's column may be exaggerated a thousand feet or so at the bottom. Moreover, Irving's section makes no allowance for possible faults except for a few minor ones that Marvine estimated.

On the whole the coincidence is fairly satisfactory, and warrants us in saying that we have represented on Isle Royale practically the whole of the Copper Range as it exists from the Central mine to Portage Lake.

At Portage Lake Irving estimates 11,000 feet of upper sandstone down to the first known diabase (the true thickness of which part of the section is very uncertain, depending as it does upon very

uncertain dips), plus 11,680 feet of the lower Keweenawan, which latter is in tolerable harmony with our section.

§ 5. Isle Royale and Minnesota cross-sections compared.

When we come to compare our rocks with their nearest neighbors and allies of the Minnesota coast, there is much more uncertainty. In the first place I am not personally acquainted with these rocks, having made only a few trips around Duluth, and having sailed in a steamer up and down the coast. Fortunately, on this latter occasion the weather was beautiful, so that the steamer could go near shore and stopped frequently for mail and fish.

I do not pretend to be able really to geologize under such circumstances, but I would suggest tentatively, (1) that the faults noticed by Irving, transverse ones as well as those mentioned by Lawson as possible (Bull. Min. Geol. Survey, No. VIII, Laccolitic Sills, p. 33), might seriously affect Irving's estimates of thickness. Faults of the kind we have found on Isle Royale, running nearly north, must play havoc with the stratigraphy, if there is no way of estimating their effect, along a coast trending in the direction of the Minnesota coast. Moreover, if they are of the same character as the fault between drill holes Nos. XVI and XV, throwing the east side up (and such is the character of the faults referred to by Irving on pages 311, 312 and 329), the effect is to increase the apparent thickness of the column, as we approach the upper beds from the west, and to decrease the apparent thickness of the column, as we pass from the upper beds toward the east. Thus the apparent thinning of the column in going east, which Irving notices and finds hard to account for (pp. 294-295 *et passim*), may be in part perhaps explained. Irving has not failed to notice these faults; indeed some of them are obvious from the steamer, but it is a question whether he has given them their full stratigraphic value. It has been for some time a current rule with geologists not to allow any more faulting than can be proven. Now, unfortunately, a fault is of a very retiring disposition, and therefore it is difficult to get proof of it. We are therefore *morally certain to make an error* in following this rule, and it is a question whether we ought not, if we find a certain class of faults in any region as often as there is a chance to obtain the evidence

of them, to compute and always keep in mind how much effect other similar but unproven faults may produce.

(2) It seems highly probable that, just as has been shown by Mr. Hubbard, in subsequent pages, for Keeweenaw Point, so here there is much more intrusive felsite than Irving realized. Such is certainly the general appearance. I submit for example that the figure and description given by Irving, on p. 323 (*loc. cit.*), would be even more natural, if we supposed the felsite intrusive.

I shall not attempt then any close numerical correlation with Irving's enormously thick Minnesota column. Yet I think Lawson has gone much too far in reaction, for I have had his ideas in mind and have examined my column with them constantly in view. We have shown a thickness of at least 7,000 feet of the Keweenawan series on Isle Royale with neither top nor bottom reached, so that the few hundred feet allowed by Lawson is likely to be far within the truth. (Anorthosytes, Bull. Minn. Geol. Sur., No. VIII, 1893, p. 21.)

I sincerely hope that the cross-section here given may be a key to some Minnesota geologist to help unlock the more complex stratigraphy of the north shore of Lake Superior.

Beginning then, at the top of Irving's series, the Temperance River group, VIII of map, Plate XXVI, ad VI of text, p. 268 (Copper Bearing Rocks, Mon. V, U. S. Geol. Survey), we find these beds described as like the layers of the Upper and Middle Keweenawan, with thin diabase flows amygdaloidal at top, more massive below; often ophites (p. 324) with ashbed diabase and diabase porphyry (i. e., our melaphyre porphyrites, and scoriaceous amygdaloidal beds) only toward the base (p. 326). This evidently matches the beds of our section down to drill hole No. VII, 81 feet. There are also in the above group numerous interbedded sandstones and conglomerates. The rock of the point at Grand Marais, with the brown color and large porphyritic plagioclases, reminds one of some of the beds immediately above No. VII, 81 feet.

The next group below, the Beaver Bay group (p. 267), is largely of coarse grained rocks, olivine gabbro with lustre mottlings (pp. 43, 322). This appears to answer very well to the Greenstone range. Of the red felsitic rock which seems to occur so abundantly in this

connection along the Minnesota coast we have only the 10-foot bed from No. VII, 81 to 91 feet, as representative, corresponding to a widespread tufa. While Irving mentions the great predominance of coarse grained rocks, he also mentions fine grained rocks and traps of which we have no representatives. They may not extend to Isle Royale, or the Beaver Bay group, to which he assigns a thickness of 4,000-6,000 feet, may include lower beds than the Allouez,—our No. VI, 363 feet, or finally these finer grained beds may have been faulted into the shore line. We are tempted to think this last suggestion true, in order to correlate the Agate Bay group with the small amygdaloidal flows underlying the Greenstone, as shown in hole No. II. Then the diabase porphyrite of the Cascade river, Sec. 26, T. 61, R. 2 W., might be the Minong trap, and the felsite of the falls in Sec. 10 (p. 295) might be the felsite that we find at the bottom of our column. These Minnesota correlations must be considered merely as suggestions, but they seem to indicate that the Keweenawan series in Minnesota is even thicker than on Isle Royale, and I cannot agree with the correlations of Isle Royale proffered by N. H. Winchell (American Geologist, XVI, 1895, pp. 160, 270, 333), which are founded on a misunderstanding of the stratigraphy. See below, § 12, in Chapter V on grain.

From descriptions of Michipicoten Island, Lake Superior, (Herrick, Tipton and Jones; Bulletin of the Sci. Lab. of Denison University, 1887, Vol. II, part 2), it would appear that the sedimentary beds there are peculiar in containing a large number of pebbles of the Huronian and Laurentian, and that the melaphyres are not highly augitic, but seem to be equivalent to the upper beds of Isle Royale, the melaphyre porphyrite or Ashbed type, rather than to the ophites. Felsites occur on Michipicoten and not high in the series on Isle Royale.

The subjoined table indicates some of the correlations suggested.

Name.	Drill hole.†	Depth in drill hole, feet.	Total thickness from 0 feet.	No. in Eagle River section.	Thickness in Eagle River section.	Copper Falls section.	Tamarack section.	Conglomerate numbers.	Distances.	Minnesota correlations.
Upper sandstone and conglomerate	XI	0	2600	2500 No. 1						
First known trap										
Small ophites, numerous sandstones	X	170	567	35	1146	1035 } 1012 }	2146	18		
Island conglomerate	X	193	589							
Transition flows, porphyrite and ophite.	X	415	806	44	1417	745	2021	17		
Scoriaceous conglomerate		426	817	63	1810	368	1639	17	883	Temperance River group?
Green porphyrites	IX	279	1100	65	2035	160			885	
Scoriaceous conglomerate—"Ashbed"		291	1112			101				
Porphyrites.						2432 } 2496 }	1081 } 500 }	16	1435 } 1445 }	
Red sandstone.	VIII	377	1525	80				*		
Porphyrites, etc.	(VII)	419	1567							
Felsite tuff.	VI	81	2055							
		91	2045							
Ophite, and the thickest ophite—the Greenstone.	VI			90	2840	Cent'l mine.				Beaver Bay group?
Conglomerates—the Allouez or "Slide"	VI	363	2310	108	4120	0	101	15	2345 } 2378 }	
Amygdaloids mainly and thin ophites	II	386	2332							
	IV	175	2570							
	(V)	133	3197							
Minong { breccia, porphyrite, trap }	I	386	4080	"Kingston" or Kearsarge?						
	(III)	426	4098							
		456	4097							
		536	4174							
Various beds ending with a thick ophite.	XIII									
Huginin porphyrite.	A	367	5194							
Ophites.	XIV	436	5200							
Felsite conglomerate.	XVI	475	5868							
Various igneous flows and conglomerates.		487	5879							
Felsite conglomerate and felsite tuff.		786	6155							
Felsite	XII	910	6400	Prays ville.						

* 67.7 above Allouez at Peninsula mine. † The depths in drill hole refer to the drill holes whose numbers are not enclosed in parentheses.

CHAPTER IV.

THE GRAIN OF ROCKS.

§ 1. Conditions that affect cooling.

There is one subject, for the study of which the possession of a suite of specimens whose position in the flow was at least approximately known, has given me especial advantages. That is the variation in the grain of the rocks. And while the methods of study require the aid of the microscope in so many cases, yet the general variation in grain is plain even to the unaided eye, and the practical interest and bearing of the subject (for example, in identifying flows or in foreseeing how far we may have to go to pierce through a belt) so immediate, that it has seemed to me well to devote a separate chapter to the subject, and not only give a few general observations which can be readily understood by anyone, but to develop the more mathematical part of the subject.

It is a well known fact of general observation that the more rapidly a solution is caused to deposit its crystals or to solidify, the finer the grain is, until if it is cooled very suddenly the atoms have no time to arrange themselves with any regularity with regard to each other, and a glass may result. The principle holds good either of solidification, or of precipitation, or of crystallization from solution. In fact there is no sharp distinction between precipitation and crystallization from solution. We call it precipitation when the separation of a solid out of a solution is very rapid, and in such case the grain of the resulting product is, in accordance with our general law, often very fine but not always impalpable. Sometimes, indeed, the highest power of the microscope cannot detect the grain.

This precipitation may be produced in various ways. It may be produced by the addition of some precipitating agent which forms

a new chemical molecule in such quantities as to be no longer soluble. This agent may be either a liquid or a gas. Thus oxygen acts upon the ferrous salts, and slowly precipitates the ferric hydrate. By an analogous process, Lévy considers the oxides of iron to be often formed in the volcanic rocks. Carbon dioxide or carbonic acid gas (CO_2) thus precipitates the calcite from lime-water. Precipitation may also be produced by the loss of a dissolving agent. The common method of evaporating mineral water until only the solids are left is an obvious illustration, but the application of heat is not always necessary. The spontaneous escape of carbon dioxide often produces precipitation, and thus the calcareous sinter around the mouths of springs is formed. Again, relief of pressure may produce precipitation, both by facilitating the escape of gas, and more directly.

Finally, the loss of heat is a frequent cause of precipitation and of solidification, one of the most obvious of all. That here, too, the size of the grain depends on the rapidity of the process, is known to every one, for candy quickly cooled is clear as glass, while the more slowly it cools the more coarsely it sugars. Good illustrations of this may also be seen in the fusible slags, such as come from copper smelting. When the slag is let run away in sheets, the quickly-cooled outside is a glass, while the center of the stream is distinctly granular. Pour the slag into a pot and let it stand so that the interior cools very slowly indeed, and we shall find there large crystals, even up to a centimeter across (Bull. Geol. Soc. Am., VI, 1894, p. 469). But whatever the process, the rule is the same: the slower the action, the coarser the grain.

In considering the solidification of rocks, we are by no means entitled to say that any of the above causes has been entirely inefficient. That the loss of heat is the chief agent in the stiffening of modern lavas we will all admit, but when we find a zone of finer grain around an amygdale, such as is shown in S. 15811 (Pl. VI) from drill hole No. XIV, 370 feet, it looks as if the escape of gas into the bubble had accelerated solidification. It is also generally understood that the more siliceous a glass or a slag or a molten rock is, the quicker it is to cool. The only thing left for us, then, is to find out what effects a given cause (say cooling) would theoretically tend to

produce, and then see how far we can distinguish these effects in practice.

§ 2. Loss of heat.

We will first take up heat, and its loss. The loss of heat and the laws of conductivity have been fully worked out, on the supposition that the conductivity is constant and the rate of flow proportional to the difference of the temperature, first by Fourier.*

Let us consider how the rate of loss of heat will vary from center to margin of a cooling mass of lava, and how the grain will be thereby affected. But first we must put in the warning that, since diffusing gas follows practically the same laws of loss as heat, the effects for these two agents of solidification cannot be separated. Nor is any account taken of the pauses and irregularities in cooling which may be introduced by the formation of new chemical combinations, attended with the liberation of latent heat. We can see, however, that such irregularities will be more likely to affect the earlier formed minerals, than that which is latest to crystallize, since it is not likely that such a chemical rearrangement of atomic affinities could take place, without altering also the character of the mineral which was forming.

In order to fix our ideas, we will suppose that we are considering a sheet of lava of indefinite extent, so that in our discussion we need only to consider one direction, that at right angles to the surfaces of the sheet, in which direction the cooling will take place. Our results will be approximately true for more irregular masses, and practically true for dikes and flows. We have then three quantities which are connected, the time since the lava arrived in its present form (t), the distances from the margins (x), within which the temperature will steadily fall, and beyond which it will at first rise; and finally the temperature at a given time and point (u). Having thus three variables, the time, the position, and the temperature, their mutual connection, if exhibited graphically, must be in the shape of a surface. Thus the main diagram of Plate IV shows such a surface for a sheet whose sides are kept at a fixed temperature. The sheet is supposed to have had the same temperature

*In the mathematical part I shall follow Riemann, "Partielle Differentiell-Gleichungen," Braunschweig, Vieweg, 1882.

throughout at the start. We are supposed to be looking in the direction of the thickness, so that the axis along which the distance from the margin would be laid off is pointing directly toward us. Then we have a series of twelve contour lines, representing, if for example the dike is 240 feet thick, intervals of ten feet up to the center. Each contour line shows the relation of the temperature, and its gradual loss with the lapse of time, for the corresponding distance from the margin of the dike.

We see at a glance that at the margin the temperature drops very suddenly at first, then steadily but very slowly thereafter, while at the center the temperature falls very slowly at first, and steadily but more rapidly thereafter. This diagram is mathematically accurate only for a particular case, but the principles it illustrates are often of wider application. We can see that in any cooling body, under any conceivably probable law of cooling the center would cool very slowly, almost not at all at first, then faster, and finally when it got down nearly to the temperature of the walls, more slowly again. This gives the form of the outside of the family of curves. It is obvious, too, that as we approach the margin the temperature would drop more rapidly than at the center. Concerning the exact extent to which the above principles can be applied, reference must be made to the mathematical appendix.

In such a diagram the relation between the vertical scale of temperature (the fixed temperature of the sides being taken as 0) and the horizontal scale of time depends upon the conductivity, and is a matter to be determined by experiment. The same diagram may be made to suit *any thickness of the sheet* and *any temperature*, by making suitable alterations in the horizontal time scale. Moreover, by laying off the temperature scale in various ways we can allow for any variation in conductivity that is dependent only on the temperature. A variation in conductivity dependent on other things, such as, for example, chemical composition varying in different parts of the flow, cannot be thus allowed for.

Now, an interesting thing will be noticed of our contour curves, that, except in the first two-tenths counting from OY, they cut any line parallel to OX at the same angle. That is to say, after the temperature at the center has fallen about one-fourth of the inter-

val between the initial temperature and the marginal temperature, *the rate of cooling at a given temperature is the same for all parts of the sheet.* For example, in the little triangle OMN the time required to drop from N to O, or as taken in this particular case, from 420° to 400° , *i. e.*, 20° in temperature, is represented by OM, and the ratio of OM : ON is obviously the same if the angle MNO remains the same.

Now can we express the effect of this law on the coarseness of grain?

It is plain that crystallization cannot take place above a temperature which would melt the mineral. It will certainly stop above a temperature at which the whole mass consolidates as a glass. It does not necessarily follow that it will take place all the time that the lava is within these limits of temperature, but the latter certainly constitute extreme limits. Now the limit thus furnished is often quite narrow, compared with the whole range of temperature to be considered (Fouqué-Lévy; *Synthese des Roches*, pp. 50 and 74). For example, Barus found for a certain diabase that it consolidated at about 1093° C., and the fusion point of augite is below 1200° C. Thus we may imagine very plausibly that, other things being equal, the grain of the augite in a basic rock will depend upon the time required to cool from 1200° to 1100° C., and if this is the same at different points the grain of the augite will be the same also.

§ 3. Zones of varying grain.

There are two other things concerning the rate of cooling that we can notice.

First, it becomes constant for a given temperature first at the center of the sheet, and the condition of uniformity in rate of cooling for a given temperature gradually spreads toward the margin or surface of the sheet, reaching there for lower and lower temperatures.

Second, the mathematical treatment shows that whenever a certain portion of the sheet has reached this condition of uniformity in cooling, the temperature thence to the center may be expressed by a sine curve. That is, if a section be cut across the surface represented in Plate IV, parallel to OY, and perpendicular to OX, the

section of the surface will give a sine curve for such part of the surface near the center as has become subject to the law of constant rate of cooling.

Our figure is drawn on the supposition that the margin of the sheet is kept constantly cool. As can be shown, we may withdraw that supposition and still express our results as follows:

If the initial temperature and conditions of cooling are such that a considerable time elapses before any part of the *sheet reaches the point of solidification*, *the rate of cooling will be the same at all points, and so far as the grain is dependent on it there will be no change of grain, but the grain will be uniform from margin to center.* By initial temperature it must not be forgotten that we mean, not any hypothetical temperature far down in the earth which the magma may have once possessed, but the temperature that it had when it came to rest at or within a given horizon with the margins that it retained. Such conditions will occur when the initial temperature of a magma is considerably more than twice the temperature of solidification, these temperatures being measured from the temperature of the surrounding medium as 0° . This surrounding medium may itself be hot and not far below the temperature of solidification, in which case we shall be almost sure to have the above conditions.

It is an easy consequence that, *the hotter the dike or sheet initially, the less will be the width of the marginal zones of gradually finer grain; also, the hotter the country rock, the less pronounced will be the marginal zone of finer grain.* This conclusion may be emphasized by the fact that in hot country rock we shall lose the convective cooling effect of water.

Thus, obviously, deep seated, *i. e.*, abyssal or plutonic rocks, will be expected to show less marginal variation in grain than more superficial formations of the same chemical character. Conversely, the broader the marginal zone of varying grain in a rock, the nearer its solidification point we may suppose the rock to have been when it came to rest. The presence of fusible porphyritic crystals, obviously formed while the sheet was still in motion, also points to a temperature not high, at the end of the period of motion, and generally we should rather expect surface flows to continue in motion until they began to stiffen. Such considerations will aid us in

checking our results. It appears *a priori* probable, therefore, that an especially frequent case for effusives may be expected to be that of solidification beginning immediately at the cessation of motion, and the grain steadily increasing up to the very middle.

§ 4. Relations of sheets with and without fixed marginal temperature.

The case where the surfaces of a sheet are kept at a fixed temperature, as would be practically true, for example, in a submarine flow, is one especially easy to solve, and is the one whose solution is graphically given in Plate IV. Mathematical investigation has also shown that the more general case, where we consider the adjacent rock symmetrically heated by the sheet, can be solved by aid of the solution for this especial case. For, suppose that the sheet or dike (whose width is $2w$) is, at its injection, of a uniform temperature (u°) and that its effect on the adjacent rocks, whose initial temperature is taken as 0° of the thermometric scale, is confined to a certain symmetrical zone (c), of which the dike occupies the center. Then it may be shown that we may find the temperatures of the zone (c), which includes both the dike (w) and the contact zone on each side, by comparison with the temperatures which a dike of equal thickness (c) would have, starting at the same time from the same initial temperature (u°), very simply as follows:

The temperature at any point of the affected zone (c) for the case that we consider the contact heated, is the average of the temperatures which two points, P_1 and P_2 (Fig. 13), would have that were

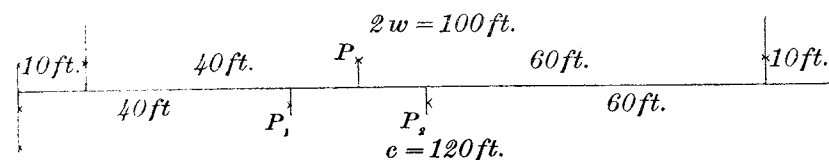


Fig. 13

Illustrates the relation of a sheet one hundred feet thick, having a ten-foot contact zone on each side, to a sheet one hundred and twenty feet thick, whose walls are supposed to remain at a fixed temperature. From these data the temperature of the former sheet may be deduced.

at the same distances from the walls of the hypothetical cold walled dike of breadth (c), as the point whose temperature is sought, is from the two walls of the smaller dike with breadth $2w$; the sum of the temperatures being taken, if said point is within the small dike; the difference, if it is outside in the contact zone.

Let us illustrate this by a numerical example. If the original dike is 100 feet thick and affected the temperature of the adjacent strata for 10 feet on each side, then a point (P) 10 feet from the center of this dike is 40 feet from one margin and 60 feet from the other. Its temperature at any time is the average of those which under otherwise similar conditions of time and temperature, two points (P_1 and P_2) would have, one 40 feet the other 60 feet from the sides of a 120 foot cold walled dike. This we may find from Plate IV. After the time 2, the temperature at 60 feet from the margin will be 626° , the temperature at 40 feet from the margin will be 556° , the average, *i. e.*, the temperature of the point (P), 10 feet from the center of the 100 foot dike, will be 591 feet.

If the 100 foot dike had had its sides kept at the uniform temperature, the temperature of this same point would have been only 487° in $(10,000 \div 14,400, \text{ i. e., about})$ two-thirds of the time, after the cooling began, as we may see by using Plate IV again, and the fact referred to in the following section, that the times of cooling of a 100 foot cold walled dike and a 120 foot cold walled dike are as the squares of their linear dimensions.

We thus see how much the heating up of the walls retards the cooling of the dike. Hence lavas poured forth or intruded where there is a chance for aqueous convection, will show more marked effects of rapid cooling and solidification.

We may also remark that if one side of the sheet were bounded by an absolute non-conductor, there would be no cooling in that direction, and we could consider that surface as the center of the flow from which the cooling takes place. Such considerations give us a clue to the kind of effect which non-conducting walls produce.

Another example: Let the point whose temperature is sought be 5 feet outside the 100 foot dike. The distances to its walls are then 105 and 5 feet; the corresponding temperatures in the 120 foot dike (the temperature at 105 feet from the margin is the same as at 15

feet) are 246° , and subtracting $84^{\circ} = 162^{\circ}$, whence the temperature sought is 81° (at same time and under similar circumstances).

In the same way we find the temperature at the margin of the 100 foot dike at the same time to be 160° .

This enables us to reduce all practical questions immediately to that of a sheet which has little or no effect in heating the adjacent rocks, and as that is the case which is of immediate practical application to the rocks we are studying, we shall confine farther attention to this particular case alone, merely remarking in passing that in the case of heated walls the temperature at the sides of the hot injected dike begins immediately to cool from a point half way between the initial temperature of the dike and that of the contact zone, and these sides cool very slowly at first, more slowly than does the center of the dike when it has cooled down to the same temperature. Thus a mineral forming at that temperature might have actually coarser grain at margin than at center. Such may have been the conditions of the formation of the feldspar in some granites.

§ 5. Conditions of initial cooling.

Another consequence of the mathematical solution of the cooling problem is that if we suppose the initial temperature of the sheet uniform and the cooling symmetrical, we find that if we increase all the linear units in the same ratio, and the time by the square of that ratio, there is no change made in the temperature. In other words, *the time of cooling varies as the square of the thickness of the dike or sheet*, so that a dike 200 feet thick will cool four times as slowly, other things being equal, as a dike 100 feet thick. In case the contact zone is negligible we can say more precisely, other things being equal, that any point in a flow will take four times as long to cool as a point half as far from the margin of a flow half the size. This may be pushed to a farther conclusion. If at the time of considering the two points just described, the centers of the dikes had not cooled perceptibly, it is obvious that it would have no effect on the temperature at the two points, if we replaced the farther half of the sheet with any thickness of material at the initial temperature. In other words, so long as the center of the dike has not cooled perceptibly, the dike might be indefinitely larger without

affecting the cooling and solidification of the parts between the center and one margin, and if we should consider the smaller of the two sheets mentioned split, and sufficient matter at the initial temperature injected to make it as thick as the larger dike, this would not, up to the time that the center of the smaller dike began perceptibly to cool off, affect the grain. Hence the larger dike would have the same rate of cooling at the same distance from the margin as in the original even smaller dike. Then, *before the center begins to cool off, the time required for a given loss of temperature for any point will vary as the square of its distance from the margin*. This is practically the case where only one margin needs to be considered, and is therefore the same result as is derived by Riemann in somewhat different fashion (*loc. cit.*, pp. 8, 82, 131). Thus the ratio of cooling will steadily increase toward the center, from the time the margin attains a constant temperature to the time the center begins to cool off, and the curve indicating the time required at the very beginning for a given loss of temperature will be parabolic in form with its apex at the margin. (Pl. IV, fig. A.)

The above are some of the principles to be applied in considering the cooling of a sheet of lava. Their exact mathematical expression depends of course on exact mathematical formulæ (see appendix to this chapter), and we have given above only a popular resumé. How far they apply, must be tested by comparing them with curves expressing the coarseness of grain of various rocks, and seeing how far the curves are similar. This is the subject of the next chapter. We can, however, see that in the basic rocks they have some applicability, at least in the roughest sort of way. It is known that the great masses of plutonic rocks are coarser and more even grained in general than smaller and more superficial flows, and this is especially true when the former have perceptibly altered the neighboring rocks, producing a contact zone. We know, too, that not infrequently from a narrow glassy margin a dike will develop suddenly a certain coarseness of grain (*cf.* Lawson *Am. Geol.*, VII, 1891, p. 153), and thereafter the grain will remain nearly uniform. These facts are in general harmony with those that the theory of cooling would indicate.

APPENDIX TO CHAPTER IV.

MATHEMATICAL TREATMENT OF COOLING PROBLEM.

Let u be the temperature of any point of the sheet, at t , a certain time after the beginning, and at a distance, x , from some fixed plane parallel to the margins, which are supposed to be parallel. The suffix, o , refers to the beginning of the time considered.

The general equation of cooling is:

$$(1) \quad D_t u = -a^2 D_x^2 u$$

Of this a particular solution is:

$$e^{-a^2 x^2 t} \cdot \sin \text{ or } \cos. \alpha (x - l)$$

e is the logarithmic base = 2.718282.

By varying x and l (x and l are arbitrary constants which we can choose at will) we must build up a solution of eq. (1) which will satisfy the other conditions of our problem. Now, if we suppose that at the point from which we choose to measure our x , our origin, we are so far from the dike or sheet that at the origin the temperature remains unaffected by the temperature of the sheet during the whole time under discussion, and that on the other side of the sheet, at the distance c from the origin, the temperature is the same and equally unaffected, and if we take the temperature of the origin as the zero point of our thermometric scale, so that u is always 0 except within these limits, and assume also that the temperature of this sheet to start with (u_o) is a function of x , $f(x)$, these conditions may be expressed as,—

$$(2) \quad u_o = f(x).$$

(3) $u = 0$ if x is less than 0 or more than c , and we may build up from the particular solution above, the following equation which will satisfy eq. (1)

$$(4) \quad u = \frac{2}{c} \sum_{n=1}^{\infty} \sin(n\pi x/c) \cdot e^{-(n\pi a/c)^2 t} \int_0^c f(l) \cdot \sin(n\pi l/c) \cdot dl.$$

Suppose, as we are including the contact zone, that the breadth of the sheet is (w) and that the center of it is at the distance (m) from our origin or starting point. Then we will naturally assume that—

$$(5) \quad u_o = 0 \text{ for } x \text{ less than } m - w \text{ or greater than } m + w.$$

Moreover, for the sake of abbreviation we will write—

$$(6) \quad q = e^{-(\pi a/c)^2 t}$$

where q is a function of the time and the only one into which the time will enter.

Since $u_o = 0$ and also $= f(x)$ outside the limits of $m - w$ and $m + w$, the $f(l)$ of eq. (4) will also be 0 outside these limits, and hence the integration indicated in eq. (4) need be extended only to these limits, i. e.,

$$(7) \quad u = \frac{2}{c} \sum_{n=1}^{\infty} \sin(n\pi x/c) \cdot q \int_{m-w}^{m+w} f(l) \cdot \sin(n\pi l/c) \cdot dl.$$

Now if the temperature of the sheet is uniform at the start, u_o , and therefore $f(l)$, will be a constant between the limits indicated, and the integration can be easily performed. We shall have to change dl to $d(n\pi l/c)$, which we may do if we divide the rest of the equation by $n\pi/c$. Moreover, $f(l)$ being constant and equal to u_o , may be removed outside the integration, so that our expression to be integrated comes to have the simple form $\sin y \cdot dy$, where y is $n\pi l/c$. The integral is known to be $(-\cos y)$, that is $-\cos(n\pi l/c)$, and replacing l by the limits of integration, we have the expression

$$-\cos(n\pi(m+w)/c) - (-\cos(n\pi(m-w)/c)),$$

wherewith to replace the integral in eq. (7)

This expression may be much simplified by applying to it the formula (Chauvenet's Trig. eq. 104).

$$(8) \quad \cos(x+y) - \cos(x-y) = -2 \sin x \cdot \sin y.$$

It is thus transformed into

$$2 \sin(n\pi m/c) \cdot \sin(n\pi w/c)$$

Whence, making all the indicated substitutions in eq. (7)

$$(9) \quad u = \frac{4}{\pi} u_o \sum_{n=1}^{\infty} \sin(n\pi m/c) \cdot \sin(n\pi w/c) \cdot \sin(n\pi x/c) \cdot \frac{q}{n}$$

an equation particularly easy to remember from its symmetrical relations with regard to x , m and w . It is obvious, as u_0 is simply a factor of the whole expression for u , that *increasing the initial temperature increases the temperature at any time and place in the same ratio*.

If we increase m , n , x , and c in the same ratio, the equation will not have the value of its last half altered, since only the ratios are involved, except in the term q , which, on turning back to eq. (6), we see involves c . We can restore q to its value by increasing t in the square of the ratio in which c is increased. Hence it follows that: When the linear scale of the phenomena is doubled, that is, the dike or sheet of twice the size, and the external zone whose temperature is affected also doubled, it will take four times as long for a point in corresponding position to reach the corresponding temperature.

This is the foundation of the principle referred to on page 114.

Now let us take up the special case where the walls of the sheet are kept at a constant temperature, so that the breadth of the contact zone is 0. In such case eq. (9) becomes

$$(10) \quad u = \frac{4}{\pi} u_0 \sum_{n=1}^{n=\infty} \sin^2(n\pi/2) \cdot \sin(n\pi x/c) \cdot \frac{q^{n^2}}{n} \text{ when } w = c/2 = m$$

Now $\sin^2(n\pi/2)$ will be alternately 1, 0, 1, 0, according as n is odd or even. Hence the series for eq. (10) expanded will be

$$(11) \quad \frac{\pi u}{4 u_0} = q \sin(n\pi x/c) + \frac{q^9}{3} \sin(3\pi x/c) + \frac{q^{25}}{5} \sin(5\pi x/c) \dots +$$

This is the equation whose numerical solution has been calculated out for twelve different ratios of x/c , and for values of q ranging from 0.99-0.10. It is obvious from a glance at eq. (6) that at the beginning, when t is 0, q will be equal to $e^0 = 1$. In the same way, as t becomes larger, q becomes smaller and at length approaches 0. The whole range of q is then between 1 and 0, so that by substituting the values of q given, we can get a sufficiently complete idea of the variation due to it. It is obvious, too, that as soon as q^4 becomes so small that it is negligible with relation to q , the series of eq. (9) and (10) will reduce to their first terms. Suppose for example that q is 0.10, then $q^4/2$ is 0.000,05. In eq. (9) the q term is multiplied by three sines, but as the sine of twice an angle cannot possibly exceed twice the sine, the whole

second term must be less than 0.000,4 of the first. This gives some idea how rapidly the series converge when q becomes small, i. e., after a little time has elapsed. Through this period

$$(12) \quad \pi/4 \cdot u/u_0 = \sin(\pi m/c) \cdot \sin(\pi x/c) \cdot \sin(\pi w/c) \cdot q.$$

At any given time, (i. e., q being considered constant) the temperatures will vary for various values of x in the form of a sine curve which touches 0° at $x = 0$ and $x = c$, in accordance with our original condition (eq. 4). Such curves will be sections of the surface of Plate IV perpendicular to the axis OX , toward the right hand end of the surface. If, while q and the time vary, we assume a fixed and given ratio of $x : c$, a section of the surface becomes a logarithmic curve, which is what the curves of Plate IV tend to become toward the right, curves which represent sections of the surface parallel to OX , while the sine curves would be perpendicular to OX .

If, moreover, we seek $D_u t$, differentiating both sides of eq. (12) and remembering that t is involved in q ,

$$(13) \quad \pi/4 \cdot u_0 = \sin(\pi m/c) \cdot \sin(\pi x/c) \cdot \sin(\pi w/c) \cdot q \cdot D_u t \cdot (-(\pi a/c)2)$$

or substituting from eq. (12) so as to eliminate x , divide through both sides of eq. (13) by the corresponding sides of eq. (12), and we have

$$(14) \quad 1/u = -(\pi a/c)2 D_u t.$$

In other words, the variation in the time required for a given small change in temperature is inversely proportional to the temperature, so that the lower the temperature the greater the time required for a small change, while *the rate of change of temperature is independent of the position of the point*, in this sense that at a given temperature heat is lost at the same rate, wherever the point considered may be. This, it must be remembered, is only true after such a time that the series of equations (9) and (11) may be represented by their first terms, after which time obviously, therefore, the grain will be independent of the position of a point, so far as the grain is dependent on the temperature or its change.

Removing this condition now, we will return and see what can be done toward simplifying eq. (9), so that its solutions may be easily derived from those of eq. (11). This we can do in case the contact zone is symmetrical, so that we can write—

$$(15) \quad m = c/2.$$

The only part of (9) that needs remodelling are the sine terms. Otherwise the expressions (9) and (11) are similar. Therefore we will take $\sin(n\pi m/c) \sin(n\pi w/c) \sin(n\pi x/c)$ and remodel it by substituting (15) and writing $z + m = z + c/2$ for x , in which case z will be the distance of the point from the center of the sheet. Making these substitutions we have: $\sin(n\pi/2) \sin(nw/c) \sin(n\pi(z + c/2)/c)$

$$(16) \quad z = x - m = x - c/2.$$

Now by Chauvenet's Trigonometry (36) from $\sin(n\pi/2) \sin[n\pi(z/c + 1/2)]$ we get $\sin(n\pi z/c) \cdot 1/2 \sin(n\pi)$ (and this is 0 for all whole values of n which alone need to be considered) + $(\cos(n\pi z/c) \sin^2 n\pi/2)$.

Now out of this last expression we can take $\cos(n\pi z/c)$ and combine it with $\sin(n\pi w/c)$, by Chauvenet (101), and we have for the remodelled eq. (9).

$$(17) \quad n = \infty$$

$$u = \frac{4}{\pi} \cdot u_0 \sum_{n=1}^{\infty} \sin^2(n\pi/2) \left(\frac{1}{2} \left(\sin\left[\frac{n\pi}{c}(w+z)\right] + \sin\left[\frac{n\pi}{c}(w-z)\right] \right) \right) \frac{n^2}{n}$$

Or, if we write, u_{w-z} for the value which u would have from Eq. (10), if x were equal to $(w - z)$, and u_{w+z} the corresponding value for x equal to $(w + z)$, we may rewrite (17)

$$(18) \quad u = 1/2 (u_{w+z} + u_{w-z})$$

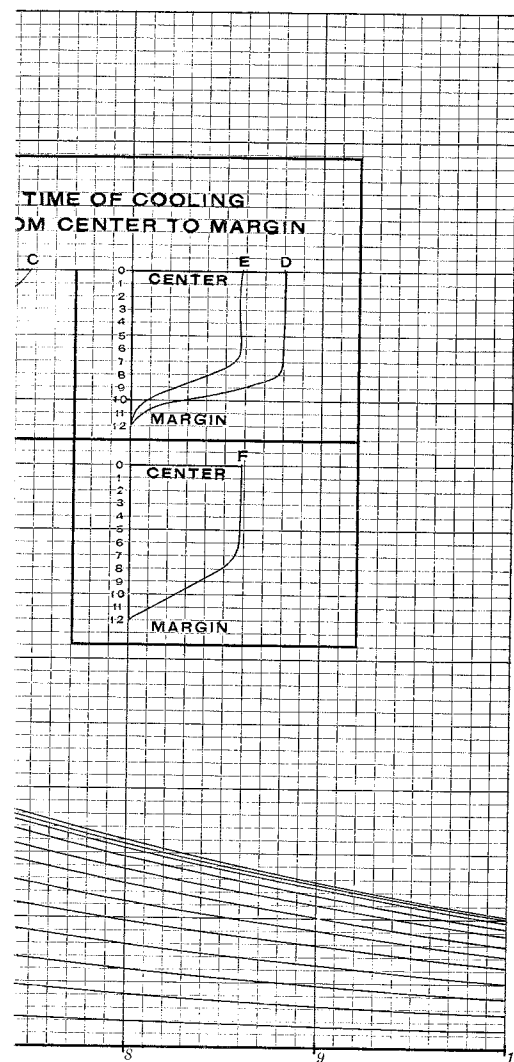
The meaning of which has been stated above (Chap. IV, § 4, p. 112). It is to be remarked that if $w - z$ is itself negative, we must consider u_{w-z} as negative, i. e.

$$\frac{u}{w-z} = -\frac{u}{z-w}$$

Practically then the numerical calculation for the sheet with margins of fixed temperatures is sufficient. In preparation for the computation and construction of Plate IV, I have compiled the table appended to this chapter, Table IV (three places accurate), showing the sums of the series of eq. (11), i. e., the temperatures, for an initial temperature of $\pi/4$, i. e., 0.7854, for points every 24th of the way across the sheet, and for values of q every tenth up to 0.9 and every hundredth thereafter.

In the same table is given $\log. q$; for, from eq. (6) it follows that

$$(19) \quad \log. q = -\pi^2 a^2 c^{-2} t$$



and is thus directly proportional to t . Thus by choosing the unit of our scale properly, i. e., equal to $-\pi^2 a^2 c^{-2}$ and laying off our abscissæ proportional to $\log. q$, they will represent the time.

Thus in the large figure of Plate IV we have the ordinates representing the temperature, the abscissæ representing the time, while the curves correspond to the various distances from the center of the dike, the outermost representing the temperature at the center of the dike at various times, the uniform temperature of the margin being taken as 0° of our thermometric scale and 0.7854 as the initial temperature.

Taken together these curves may represent the contours of the surface which connects together the three variables, time, temperature and position in the dike. Sections of this surface for a given time, i. e., perpendicular to OX, the axis for the abscissæ of time, will, near the beginning of the time, give us curves of the form familiar to us in the discussion of the cooling of the earth* (e. g., C. P. Q. in Thomson and Tait's Natural Philosophy, Vol. I, Part II, p. 477).

* In fact our problem is closely akin to that of the cooling of the earth, and the solution of our eq. (10) p. 118, may be made to depend upon that which Woodward has solved for the cooling (Annals of Mathematics, Vol. III, 1887, p. 77, eq. 10) of the earth. If for distinction's sake we represent by V_m the temperature of a point in a sheet cooling under the conditions applicable to our eq. (10) above, at a distance (x) from the margin such that x/c is m , and by u_m the temperature of a cooling globe of radius c , cooling under similar conditions—such as those given by Woodward—at a distance from the center of r , such that r/c is m (m being evidently any fraction between 0 and 1), it is easy to transform the two equations so as to show that

$$V_m = m u_m + (1 - m) u_1 - m$$

Thus

$$V_{1/2} = u_{1/2}$$

16

Numerical Solution of Equation 11.

1.00	.99	.98	.97	.96	.95	.94	.93	.92	.91	.90	.80	.70	.60	.50	.40	.30	.20	.10	q = 0.00	m.
	0.50611	0.38106	0.31736	0.27735	0.24913	0.22791	0.21115	0.19750	0.18605	0.17604	0.12197	0.09653	0.07959	0.06552	0.05227	0.03916	0.02611	0.01305	0.	1
	73460	63292	55853	50299	46043	42674	39898	37585	35607	33892	23943	19071	15767	12989	10359	07765	05176	02588	0.	2
	78291	74561	69774	65238	61345	57784	54766	52115	49802	47728	34817	28033	23371	19195	15315	11481	07654	03827	0.	3
	78516	77820	75875	73285	70511	67798	65239	62850	60630	58585	44511	36347	30336	25065	20009	15001	10000	05000	0.	4
	78539	78404	77908	76795	75318	73607	72200	69979	68189	66449	52824	43856	36835	30499	24357	18264	12175	06088	0.	5
	78540	78534	78328	78072	77426	76532	75457	74165	73100	71698	59680	50443	42665	35402	28290	21214	14142	07071	0.	6
	78540	78540	78524	78433	78208	77825	77270	76590	75798	74934	65106	56037	47730	39699	31737	23800	15867	07934	0.	7
	78541	78539	78538	78510	78453	78313	78070	77730	77291	76700	69218	60620	51962	43301	34641	25981	17321	08660	0.	8
	78540	78538	78541	78539	78522	78485	78385	78233	78017	77731	72171	64156	55305	46169	36952	27716	18478	09239	0.	9
	78536	78538	78539	78539	78536	78513	78492	78421	78335	78195	74128	66665	57718	48238	38631	28977	19319	09659	0.	10
	78535	78535	78540	78540	78539	78535	78528	78505	78460	78390	75242	68160	59176	49529	39650	29743	19829	09914	0.	11
0.78538	78538	78537	78540	78540	78540	78538	78534	78522	78492	78443	75601	68658	59664	49934	39991	29991	20000	10000	0.	12

The numbers in the table are $\pi u/4u_0$, or the temperatures if $u_0 = 0.78538$, as functions of m and q ; m indicates distance from margin of a lava flow in terms of its thickness, the total thickness being $m = 24$, and the middle $m = 12$. $q = e^{-(\pi a/c)^2 t}$ where $t =$ the time since cooling began, c , the thickness of the flow, $= 3.1415927$, and a depends on the diffusivity. Now $t = \log q / \log e^{-1} \cdot c^2 / a^2 \pi^2$, i. e., $\log t = \log \log q + \log c^2 - \log a^2 - \log \pi^2 - \log \log e^{-1}$, whence we can construct tables expressing the value of the time corresponding to q for various values of c and a^2 . The variation from 0.78538 in the lower left hand terms shows that the approximation is not complete. The table was constructed with five place tables, and checked with four place tables.

If, as according to Thomson and Tait (Nat. Phil. I, II, p. 476, $a^2 = 400$ for foot and years) and $c^2 = 10,000$, we have the times as given in the last row.

For other sizes of flow and conductivities the times are easily found by direct multiplication.

q	1.00	.99	.98	.97	.96	.95	.94	.93	.92	.91	.90	.80	.70	.60	.50	.40	.30	.20	.10
10-log q		9.99564	9.99123	9.98677	9.98227	9.97772	9.97313	9.96848	9.96379	9.95909	9.95424	9.90309	9.84510	9.77815	9.69897	9.60206	9.47712	9.30103	9.00000
log q		0.00436	0.00877	0.01323	0.01773	0.02228	0.02687	0.03152	0.03621	0.04091	0.04576	0.09691	0.15490	0.22185	0.30103	0.39794	0.52288	0.69897	1.00000
Time in years (correct to 3 places) for 100 foot sheet	0.00	0.0195	0.0394	0.0591	0.0793	0.0998	0.1204	0.141	0.162	0.183	0.204	0.434	0.694	0.993	1.348	1.781	2.341	3.130	4.477

CHAPTER V.

THE GRAIN OF ROCKS: APPLICATIONS OF THEORY.

§ 1. Preliminary observations.

From the considerations of Chapter IV we are encouraged to compare our theoretical results with the grain* of rocks as determined by observation. But there are one or two things to note first. If we suppose the solidification to begin before the rock comes to rest, those crystals which were formed before the rock came to rest are obviously not subject to any rigid law as to size in relation to distance from margin. This will include not only the really old and large porphyritic crystals, which are relics of some previous stage of solidification, but also those which were formed while the lava was in motion and are arranged in lines of flow, and this includes the small feldspar microlites which make up the andesitic groundmass. Of course such products of the period of flow may in the later period of rest be enlarged, but the centers of crystallization having been already determined, it is not clear what the resultant grain might be expected to be (see § 7).

As to the size of the porphyritic crystals we can therefore lay down no general rules. We can only say that they are there and of such a size, indicating that the magma was kept at a temperature favorable to their formation for more or less time, but all the other factors which affect the rapidity of crystallization will have to be looked out for also. But when we consider the final growth of minerals which occur porphyritically, we know that the magma was already below the upper limit of their formation. Any increase in their size due to subsequent growth must therefore conform to the laws of initial cooling. Thus between two porphyritic minerals, or between a porphyritic mineral and one not porphyritic, the final

* Throughout this chapter "grain" is used for size of grain or degree of coarseness as determined on p. 125.

growth, other things being equal, should be more prominent for that mineral that has the lower limits of crystallization.

Furthermore, it is obvious that in proportion as the temperature of the lava when the latter comes to rest is close to the bottom limit of crystallization for a certain mineral, that mineral will be finer grained. Thus a great disparity in the grain of two minerals, greater than could be accounted for by any recourse to chemical reasons, might be accounted for by supposing that the temperature at coming to rest was near the lower limit of crystallization of the finer grained mineral.

Moreover, it is obvious that the conditions of cooling in the amygdaloidal zone will be something quite outside the line of our primary investigation, except that the amygdaloidal zone implies glass, and therefore also that the temperature sank below the glass-forming point before the molten mass could entirely crystallize.

§ 2. Method of observing grain.

So far, although we have assumed that the size of grain depends on the rate of cooling, or more exactly, on the time which passes while the magma is between the temperature at which a given mineral would fuse, and the temperature at which its molecules would solidify as glass, we have not considered how we must measure the size of grain, or whether it is directly proportional to the rate of cooling or to some power of that rate. Now there are two practical ways in which we may measure the size of grains, and one impractical way. First, we may select grains of the average diameter, or, second, cross-sections of average area; or we may take the average bulk, this last method being the impractical way. But if the form of the grains is the same in the coarse as in the fine rocks, the surfaces will be as the squares of any one of the linear dimensions and the volumes as the cubes thereof. Thus in a way the two questions, as to the relation of grain to rate of cooling and the proper method of measuring the grain, run into each other. It may be that the linear dimensions of the grains increase proportionally to the slowness of cooling, in which case it should be to the linear dimensions that we should look for comparisons. If, however, as seems rather more likely, it is the area of the surface of a grain which increases proportionally to the slowness of

cooling, since additions are made to the surface, then the area of cross-sections will also be proportional to the slowness of cooling, while if it is really the volume which is proportional to the slowness of cooling, we shall have to cube the average linear dimensions.

Moreover, what gives us the general impression of coarseness of grain is rather the average size of the larger crystals than the average of all. There is then a gap here between theory and fact, that can, so far as I have investigated, be bridged only by an empirical law derived from observations and experiment.

The way I have practically proceeded has been as follows: I have taken three different fields of view in a thin section under the microscope, and have in each field measured the longest diameter (a) of the largest grain of the mineral whose grain I was studying, and also the diameter (ca) at right angles to it.

I have taken the average of the three readings for the mean dimensions m and cm , and then have averaged both, i. e., $\frac{1}{2} m (c + 1)$, and have also multiplied together these mean dimensions (i. e. cm^2). Let us see what the difference will be between the product of the two dimensions and the square of the mean of the two dimensions. The former is cm^2 and the latter is $\frac{1}{4} m^2 (1 + 2c + c^2)$. These two expressions will be the same if c is 1; then as c decreases, the latter expression will become greater. If, for example, c is $\frac{1}{2}$, the ratio will be $\frac{1}{2} : \frac{1}{4} (1 + \frac{1}{2})^2 = 8 : 9$, and if c is 1-6, as sometimes occurs in the feldspar laths, the ratio is 24:49.

§ 3. Effect of cooling on grain, in the augite of the ophites.

We will begin our investigations with the more basic rocks, since they have been artificially imitated by unaided igneous fusion, and we will study first the augite of the ophites, that mineral which both from its texture, and from the fact that it does not occur in porphyritic crystals, has obviously been formed during the period of rest.

Figure 14 shows the results of observations (indicated by small circles) on the Greenstone (Ss. 15245-15258), the vertical scale denoting the thickness in feet, the bottom of the bed being at the bottom of the figure, and the distances on the right of the vertical scale proportional to the area of the augite patches, computed as described in Section 2, in square millimeters. From the point representing the coarsest grain, parabolas are drawn for com-

parison to the top and the bottom of the bed. It will be seen that the points indicated by the small circles (the crosses and dots are explained below, p. 127) lie parallel to the curve, especially for the bottom part, but they lie uniformly a little below it, indicating a

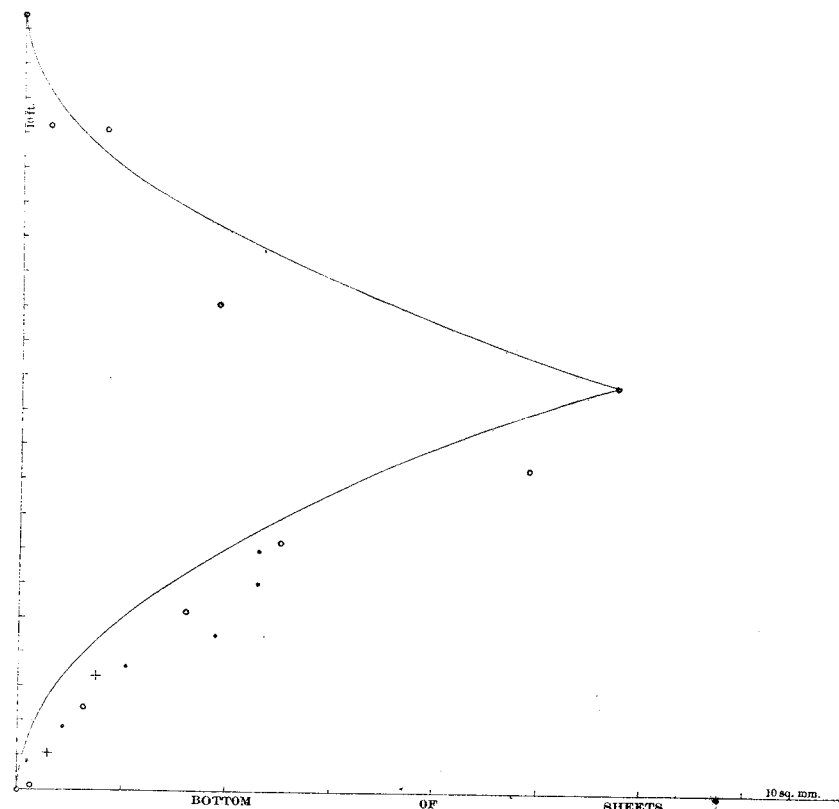


Fig. 14

Illustrates the relation of the area of cross-sections of augite crystals to the distance of the crystals from the bottom of the sheet; different signs indicate observations on specimens from different sheets, as follows:

- ° The Greenstone, Drill hole No. VI, 130-363 ft.; Ss. 15248-58.
- Drill hole No. XIV, 202-367 ft.; Ss. 15804-10.
- + Drill hole No. XVI, 696-786 ft.; Ss. 15934-44.

little coarser grain quite down to the margin; that, in other words, there was a small contact zone. If we start the parabola ten feet below the bottom of the sheet, and run it to the center of the sheet, —and it may well be that the coarsest sample taken by us is in

reality a few feet from the coarsest part of the bed—we shall get a curve of even more exact coincidence with the points of observation; both for the grain above, and for that below the middle of the bed. Now these observations indicate a grain increasing in size quite to the center of the bed, with no appreciable zone of uniform grain in the middle, and this remains true whether we compare linear, surface, or volume dimensions. (For if the grain at two points is equal, it will be equal whether we compare it in one way or the other. If, on the other hand, it is unequal, it will remain unequal, the only difference being in the rapidity of the increase from one point to the other.) Such a condition of things indicates a rate of cooling decreasing from the margin even to the center of the sheet, and as we have seen (pp. 110-113), this means that the rock solidified during the very first period of cooling, immediately after coming to rest.

Now let us see if other considerations tend to verify and support this conclusion, or to contradict it.

(1) The observations plotted show not only that the increase in the size of the grains in the bed continues from the margin to the center, but also that this increase, *measured by area of cross-section*, follows a parabola, that is, that the area of the cross-section of the grain varies as the square of the distance of the latter from the margin. A similar law, as we have seen (p. 114), holds for the initial time of cooling, and is thus not only a verification of the conclusion above,—that the rock solidified during the first period of cooling—but leads to the conclusion that *the area of cross-section or surface of the grains varies directly as the slowness of cooling*.

(2) If this be true, the rate of cooling and the size of grain ought to be independent of the size of the sheet, in sheets which have thus solidified before the center had appreciably cooled. The only way in which we can test this law is to compare other ophites of apparently similar composition but different size. In Figure 14 similar observations for the 157* foot flow, drill hole No. XIV, 202 feet to 367 feet (Ss. 15804-15810), are indicated by dots, and those of the 80* foot flow, drill hole No. XVI, 696 feet to 786 feet (Ss. 15943-15944), by stars, and it will be seen that they show a very fair coincidence with the theory. These flows were not chosen to fit, but

* These figures represent the actual thickness.

because they fill well the requirements as to the varying size. Other observations have also been computed, and harmonize as well as these. In a general way we must say for our ophite flows that, relatively speaking, their solidification took place almost immediately after they came to rest; that they were not superheated, and that the grain, so far, at least, as the augite is concerned, is measurably independent of the size of the flow, but dependent rather on the distance from the margin. And if the areas of the augite sections vary as the squares of their distances from the nearest margin, then the square roots of the areas, or *the linear dimensions of the augite patches are directly as the distance from the margin*; a very simple law, the verification of which by field observations will tend to sustain the law from which it is derived. In Figure 15 we

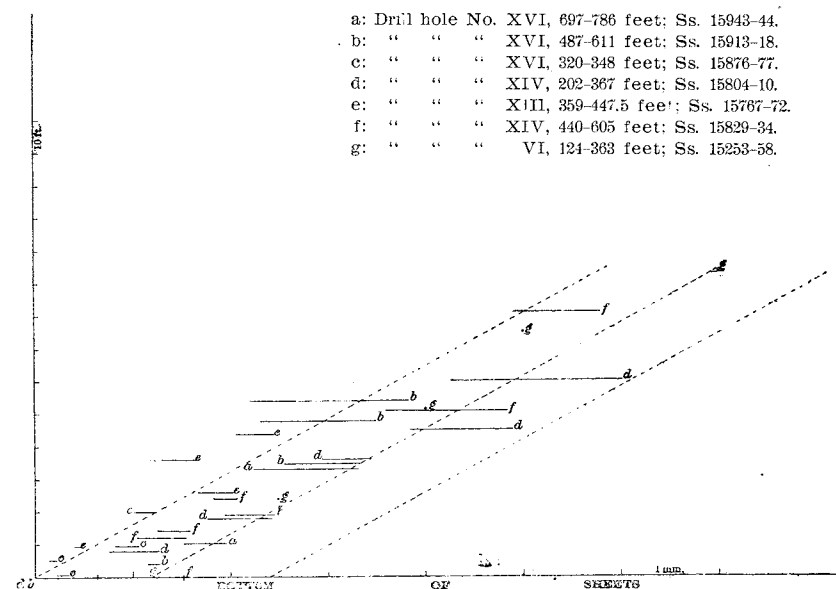


Fig. 15

Illustrates the relation of the linear dimensions of augite crystals to the distance of the latter from the bottom of the sheet, in ophites; letters a, b, c, etc., indicate specimens from different sheets.

have a diagram showing the average or mean of the greatest dimensions of the augite mottlings for a number of thin sections from the respective bottoms of sheets of ophite, and also the average or mean of the dimension at right angles to this, by straight lines

drawn at right angles to the scale of thickness, each line connecting two points, which by their respective distances from OA represent the two means above referred to.* The square roots of the respective products of these means, i. e., the quantities which should be in direct ratio to the distances from the margin, will be represented by points below the middle of each line. These latter points ought to lie on one straight line for any one sheet, if the law is strictly true. These points are noted by dots lettered g for the Greenstone. The length of the lines gives some idea of the probable range of error. The tendency to arrangement along a line is evident and, with the exception of e, the rate of increase is not far from that in the Greenstone (and e has some exceptional characters—an unusual amount of feldspar with a glomero-porphyrific tendency). A line from the 7 mm. grain of the Greenstone (at 96 feet from the margin), to the 1.25 mm. grain near the foot wall, will pass close to the intermediate values, will cut most of the lines, and, if we allow for an error of one millimeter in our estimates of grain, will cover practically the grain for all the sheets but e. It will lead to the approximate expression, derived from the equation of a line through two points,

$$y \pm 1 = 0.06 (x + 1)$$

where y = linear dimensions of grain in mm. and x = distance in feet from margin of bed. Figure 16 covers most of the remaining observations on ophite sheets (apparently undisturbed by slips, with well defined margins) on Isle Royale, even if only in part ophitic, and it will be seen that most of them are covered by the formula above, if we allow as above an error in y of 1 mm. This allowance is necessary in order to offset the small number of observations we have used in obtaining the average dimensions of the augite, to offset the variation in some slight degree in chemical composition, and, what is especially important, to offset the varying amount of contact zone, the grain of the larger sheets like the Greenstone being properly reckonable from the margin of this zone.

Except in the case of the Greenstone we have not given the observations for the upper half of the flows. These observations, however, show the same law, though somewhat more obscurely. The effect of the amygdaloidal zone and magmatic differentiation, and possibly original irregular distribution of temperature is shown in

* The lines are lettered with reference to the sheet from which they are derived.

fairly frequent variations from the general law, yet not frequent enough but that the general fact that they follow the same general law can be clearly seen.

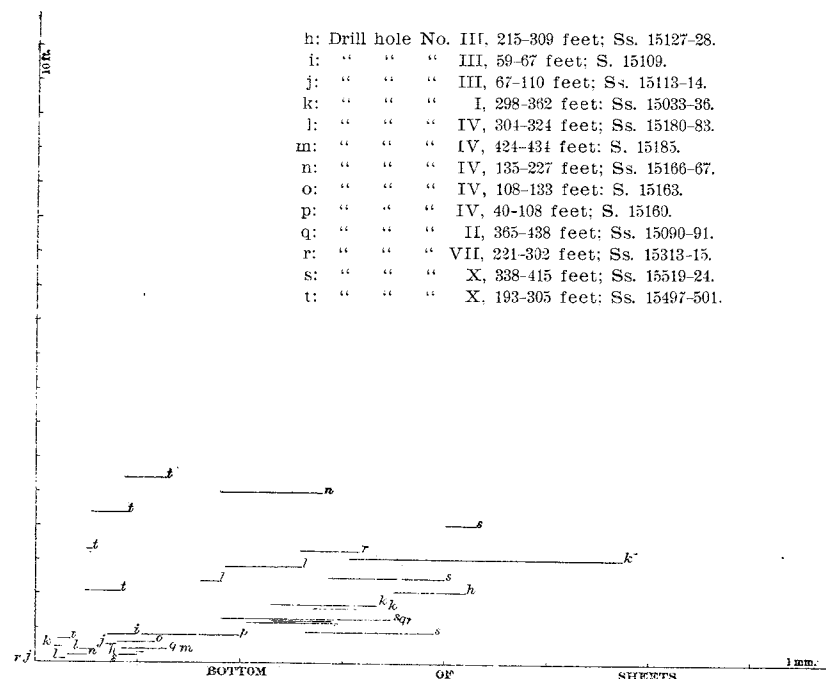


Fig. 16

Illustrates the relation of the linear dimensions of augite crystals to the distance of the latter from the bottom of the sheet, in sheets not represented in Fig. 15; letters h to t indicate specimens from different sheets.

It will be noticed in figure 16, that (Ss. 15489-15501) t cannot be given at all the same rate of increase as the Greenstone, though the increase is still linear. The reason is not far to seek, and this bed was put in only for comparison. The feldspar is mainly andesite ($Ab_5 An_5$) and the augite is not in ophitic patches, but often in patches of granules, and often much less in quantity. Again, s (Ss. 15513-15523) is another bed with a different feldspar from that of the normal ophites. In fact, a detailed discussion would enable us, for each particular composition, to confine much more closely the limit of variation from the law.

(3) To the conclusion that the solidification of the ophites belongs to the first stage of cooling, the whole magma or molten mass being already nearly down to the temperature of solidification as glass, point not only the above mentioned facts, that the area of the grains increases in the square of the ratio of their distance from the margin, and that the distance from the margin being the same, the grain is measurably independent of the size of the flow, but a farther fact points to the same conclusion, namely, the fact that we have right near the middle of the Greenstone, in S. 15253, a big porphyritic crystal of feldspar (somewhat more basic, to be sure, than the usual feldspar), for, according to Fouqué and Lévy (*Synthèse des Minéraux et des Roches*, p. 74) it is only within a narrow range of temperature that the crystallization of feldspar will take place while the augite is still molten.

(4) There are a number of other reasons, in the variation in grain of any one constituent and in the relative grain of different constituents (cf. § 6), for believing that the Greenstone is a flow and not an intrusion; and also in its general stratigraphic relations, i. e., its appearance uniformly at a given horizon in the series, its great lateral extent, its slight metamorphism of the underlying conglomerate, etc., etc. Now if it is a far- and wide-spreading flow, we should expect it to have continued in motion until it was so far cooled as to become viscous and to be on the point of stiffening, in which case the solidification must have followed immediately after it came to rest, a conclusion in harmony with our previous arguments.

(5) As we have spoken of intrusions, it will be interesting to compare the curve of the grain, Fig. 15, with that of an undoubted intrusion. We give, therefore, in Fig. 17, corresponding curves for two dikes, one of which (Ss. 11421-11426, near Marquette in the Huronian) is, as nearly as can be judged petrographically, of similar composition to the ophites. We see at a glance that the curve is of an entirely different type, and no change in measuring the dimensions can make it similar. The belt of uniform grain in the middle must remain uniform, however we measure the grain. In this respect it is more like a plutonic rock. The decrease in size of grain toward the margin shows that the dike was injected into comparatively cold rocks. There is no indication here of as much

contact effect as in the much larger Greenstone. But the curve of this dike can be matched by a curve, Plate IV, curve F, which shows the rate of cooling sometime after the cooling has begun, so that the temperature has dropped about half way. Hence we may conclude that this dike had considerably more than the temperature of crystallization of augite when the dike came to rest;

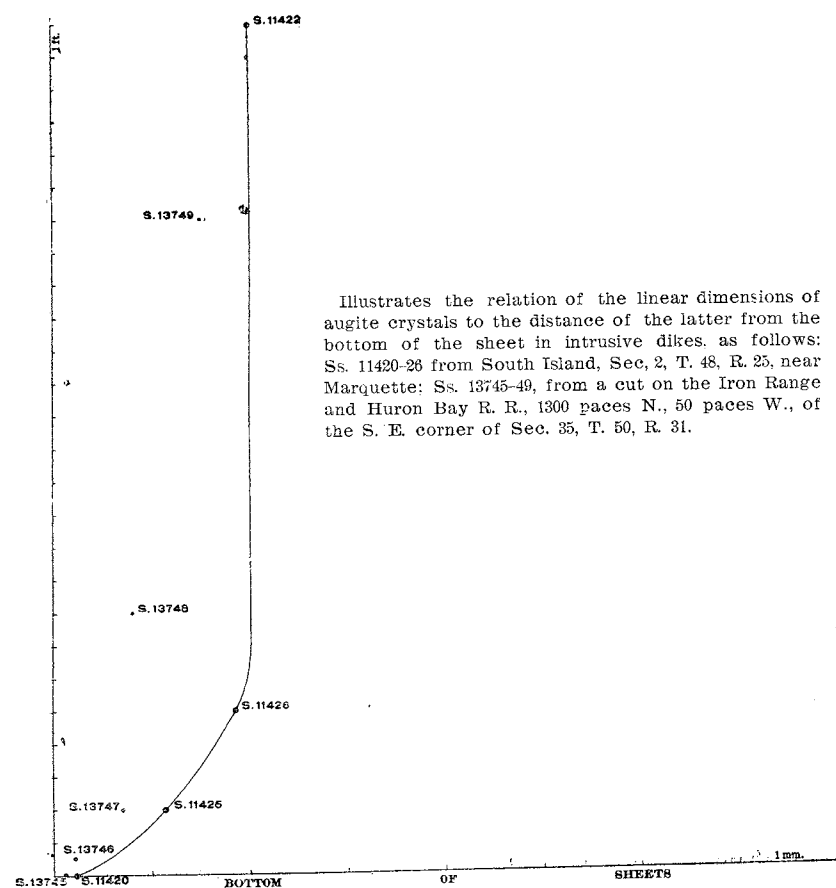


Fig. 17

this might well have been the case, for we know that lavas sometimes attain temperatures of over 1200°C . We can even estimate from the shape of the curve the ratio of the initial temperature to the temperature of crystallization of augite.

(6) Farther verification of our conclusions will come, if we find that the grain of the other minerals is in accord with the conditions of cooling indicated by the grain of the augite.

§ 4. Effect of cooling on grain, in the feldspar of the ophites.

In Fig. 18 we have represented the grain of the feldspar in the same sheets as were represented in Fig. 14, and the same symbols are used. The only difference is that the scales for the size of grain vary as indicated in the figures, and the comparative parabolas in Fig. 18 are drawn to indicate an appreciable size of grains at the margin, for we find, as a matter of fact, that even close to the margins, both upper and lower, the feldspar has an appreciable size. The rock in fact has a porphyritic texture. The cause of this appreciable size at the margin is not, as in the augite, to be ascribed to a contact zone so much as to the fact that the feldspar began to crystallize before the lava stopped flowing, i. e., before the period of rest. This fact is, of course, indicated in all cases where we can detect traces of a fluidal arrangement in the feldspar.

We must, therefore, subtract from the size of the feldspar whatever size it may have attained before the sheet came to rest, and even then the presence of so much pre-crystallized feldspar might seriously affect the law of grain. However, the generally concave curve is plainly enough indicated in two of the sheets. In the other one there is the utmost irregularity, the difficulty being that the sheet is markedly porphyritic at the margin, and the feldspar tends to be glomero-porphyritic by collecting in nests, so that the separation of the older and younger feldspar, and the estimation of their respective sizes is in this case unsuccessful. In general, the feldspar laths are so narrow, so fond of attaching themselves to each other by the side (pinacoidal), that it is a matter of difficulty to get accordant results.

Comparing the feldspar and the augite of the Greenstone, we get some significant results.

Below the center of the sheet there is more of a tendency for the grain of the augite to exceed, and for the feldspar to fall below the theoretical curve, while above the center the feldspar is markedly larger, and the augite falls short. This reciprocal relation is more strikingly brought out in specimens 15250 and 15249, the former abnormally augitic, the latter abnormally felds-

pathic—the two in reciprocal relation. These specimens correspond respectively to the dark and light types of diorites (Pumpelly's gabbro) which Marvin distinguishes in this very flow (Geol. Sur. Mich., I, Pt. II, pp. 133-136). As he says, they occur in alternating bands, sometimes but a few inches thick, and not sharply separated. I am convinced that they represent a magmatic segregation or differ-

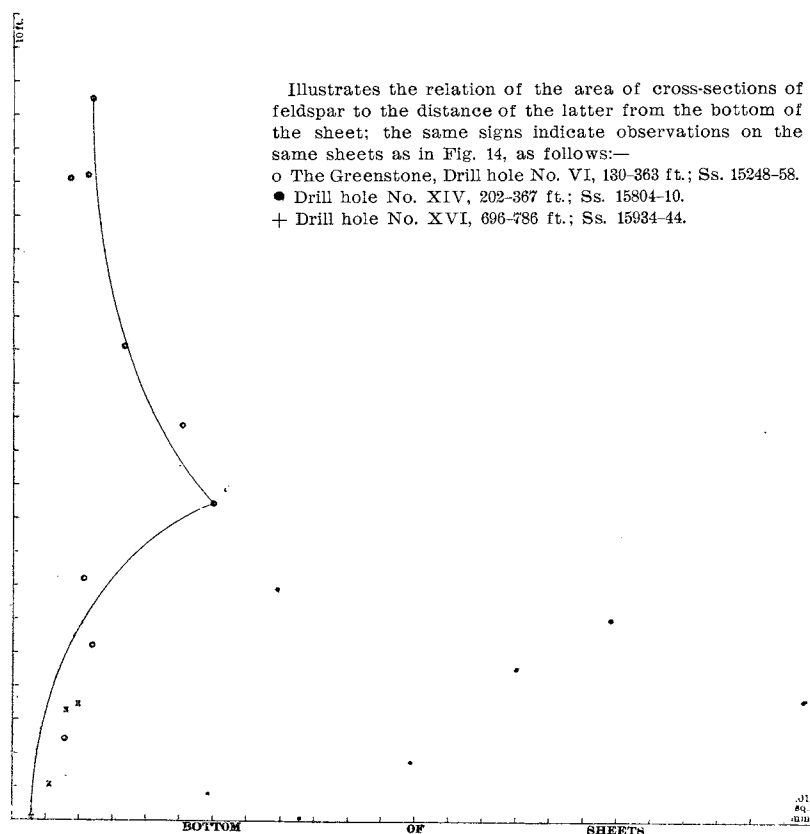


Fig. 18

entiation of some kind, or an original lack of homogeneity. If we suppose a tendency of the feldspar or feldspar molecules to rise toward the top of the sheet and of the augite substance to settle, and imagine the layers to be stirred and interknaded in the process of the flow, we shall frame a hypothesis which will account

for all the phenomena. For the present, however, our chief object is to point out the indication of another law than that of cooling, namely, that of chemical composition, as influencing the size of the grain. So long as the composition of the flow is tolerably homogeneous this factor can be but of minor importance, but in flows of varying composition its influence may be large, and remains to be investigated. See the discussion of the analyses of specimens 15515, 15519 and 15523, and compare in Fig. 16 the grain of the sheet from which the material for these analyses came.

§ 5. Grain of other constituents of ophites.

When we come to the remaining original and important ingredients, aside from the augite and the feldspar, we find the determination of grain more and more difficult. In the first place, with one or two exceptions (Ss. 15827 and 15807), the olivine is all altered to serpentine or at times to that reddish micaceous substance, which has been often described (Ros. Mik. Phys. 1896, II, p. 963), and is at least akin to Lawson's iddingsite. This alteration does not make it by any means always impossible to recognize the olivine outlines, but it does make it hard always to be sure that we are rightly drawing the line between olivine and augite, and renders it very frequently uncertain whether a given patch of serpentine represents more than one olivine grain.

With the iron oxides we have similar difficulties. They occur replacing the olivine, sometimes secondary, and sometimes apparently not, at any rate making up together a unit, so far as grain is concerned. Moreover, being opaque and isotropic, it is not possible to distinguish with any certainty granular aggregates, twinned aggregates, and allotriomorphic forms. But making all allowance for greater uncertainty in observations on these minerals, some things seem reasonably certain. The laws can be made very obscure by statistics, and general impressions gathered from observation of the sections must supplement them.

In the first place then, there is ample evidence of the formation of the olivine at an early day before the augite and feldspar, that is, before the period of rest. In many cases it appears to have been corroded. It is porphyritic and of noteworthy size, therefore, even up to the margin, both at top and at bottom. Then in the more augitic and olivinitic flows, as for example, specimens 15820 to

15834, there is a tendency for the grain of the olivine to increase for some distance, though interrupted by variations, and then to decrease toward the top of the flow, but in the more feldspathic flows, in which the ophitic texture is confined to the lower part of the flow, the variation in the grain of the olivine bears only a very complex relation, if any, to its distance from the margin, as is illustrated for example by specimens 15489 to 15501. Right in the middle of the sheet the olivine is often exceptionally small in some parts and large in others. The places where it is large are the coarse feldspathic spots with a doleritic texture. There are evidently other laws more influential upon its grain, than those of cooling.

In review then, we may say that in the ophites the augite, the last mineral formed, shows by its size of grain the effect almost exclusively of cooling, and conforms to the laws of initial cooling from a uniform temperature (pp. 111-112); that all the other minerals appear to have been previously formed or in process of formation and show only faint traces of those laws, but that their grain and appearance and the stratigraphic evidence are quite consistent with the hypothesis that the lava was cooled down almost to solidification before it came to rest.

§ 6. Verification on the Greenstone elsewhere.

Of course the ultimate test of these theories, as of all theories, must be verification. If in other ophites of similar composition and similar variations in grain we shall prophesy their thickness and their effusive character, from size and variation of the grain, and farther investigation shall establish our prophesies to be conformable to the facts, every such case will strengthen our faith in the theory and widen the sphere of its application. To begin with, let us apply the theory to the flow on Keweenaw Point, which we have supposed to be the same as the Greenstone of Isle Royale. In Marvine's description of this bed (Geol. Sur. Mich., I, Pt. II, pp. 133-136) the gradual increase in grain down from the top and up from the bottom is clearly stated, until the bed begins to break up into lighter and darker, respectively more feldspathic and more augitic layers. From that point it is harder to trace the grain, either in the field or in his descriptions, and exact indications of size of grains are wanting, but the statement that lustre mottlings

toward the top of bed No. 108 (the lowest 412 feet of the Greenstone), "often over the space of nearly two inches square, all catch and reflect the light simultaneously," would certainly indicate that the patches of ophitic augite (which Marvine calls hornblende) were on the average over an inch, i. e., more than 25 mm. in diameter. Or, substituting in the formula of p. 129* $25 \pm = 0.06 x + 1$, where x denotes distance from margin; therefore distance from margin is $400 \pm$, —a sufficiently near coincidence.

On the road from the Central mine on Keweenaw Point to Copper Falls, I found the mottling in the Greenstone as coarse as six knobs to the foot, or about 50 mm, which would indicate by the same rule a point about 800 feet from the margin, or a bed 1600 feet thick more or less, a result in agreement with the facts so far as I know them. (See Part II.) Again, samples from Marvine's bed No. 91 (exposure up on the hill) give mottlings from two-tenths to three-tenths of an inch, indicating a distance from the margin of 80 to 120 feet. Marvine's bed No. 93 seems to be still coarser, with a mottling 1.5 in. x 0.8 in., etc., that would indicate a distance from the margin of over 400 feet; whereas it really is only about 200 feet. The point where the specimen showing the mottlings was taken is in the part of the bed where the light and dark types alternate.

Marvine's bed No. 96 has weathering knobs of about an inch in diameter with mottlings showing a length of 0.6 inch, thus indicating a distance from the margin of 300 feet to 400 feet. A large sample from the Greenstone, whose exact location is unknown, has an average grain of 1.07 in. x 0.75 in., indicating a distance from the margin of 360 feet, and a total thickness of over 720 feet.

Above the Phoenix mine, along the horsepath, I noticed the grain increase at the crest of the range to about two knobs to the inch. This is at a point about 100 feet above and 400 feet northwest from the bottom of the flow, or about 265 feet vertically above the foot of the bed, the dip being about 26° . The grain would indicate a distance from the margin of about 200 feet.

The general agreement in the cases above cited is as good as one could expect from the rough character of the observations, with the exception of perhaps those at Marvine's bed No. 93.

* Which we may also write for rough, naked-eye observations, $400 \times (\text{size of mottlings in inches}) = \text{distance from margin in feet}$.

Turning to Irving's "Copper-Bearing Rocks," at page 42 we find lustre mottlings described in a "gabbro," which we have already mentioned as a possible equivalent of the Greenstone, with "brassy diallage faces which are often as much as two inches across," which would point to a bed probably not less than 1600 feet thick (possibly not intrusive but effusive). So, also, the rock illustrated in Plate IX, of the same work, should come from a sheet at a point not less than 90 feet from its margin; if it is comparable to the Greenstone, more probably 110 feet. We have no data at present to show whether these deductions correspond with the facts.

§ 7. Relative size of various constituents.

Before we leave the ophites to consider the possibility of tracing the effect of cooling in other rocks, we have one other point to consider. We have discussed the grain of each constituent, but we have not discussed the relative sizes of the various constituents. These are not capable of being well expressed on the same scale in one diagram,—the difference is so very great,—but we can observe that in the augite diagram, Fig. 14, the scale for the grain in areas is from 1:25 to 1:50, as compared with that for the feldspar areas in Fig. 18. A corresponding linear ratio would be from 1:5 to 1:7. But while the ratio of the area of the feldspar to that of the augite is to be measured in hundredths, for the Greenstone and its immediate allies, it is by no means necessarily true of all ophitic sheets. Take, for example, the sheet from drill hole No. X, 338 feet to 415 feet. The feldspar here is, to be sure, markedly porphyritic, but the general analysis of the rock does not indicate any more feldspathic material than does Foster and Whitney's old analysis of the Greenstone (F. & W. II, p. 88). But taking all the feldspar in the bed, without trying to separate out the porphyritic portion, the grain is very much coarser than in the Greenstone. Toward the bottoms of the two flows, moreover, there is no essential difference in the optical character of the two feldspars, so that it seems quite likely that the reason for the relative smallness of the feldspars in the Greenstone lies in the fact that the sheet did not cool enough in transit to produce any appreciable amount of porphyritic crystals, for they occur only sparingly, and when it finally came to rest, since the temperature of solidification is somewhat higher for the feldspar than for augite, the feldspar had to

form even more rapidly than the augite did. Whether this be the true explanation or not, the fact that the feldspar is very much smaller than the augite is another fact quite in harmony with what we have concluded to be the conditions of cooling of the Greenstone (p. 131).

In the dikes cutting the Huronian, already alluded to (p. 131), the feldspar and augite are much more nearly of the same size, although the mineral composition appears to be about the same, and this is what we should expect.

§ 8. Effect of cooling on grain in the more feldspathic rocks.

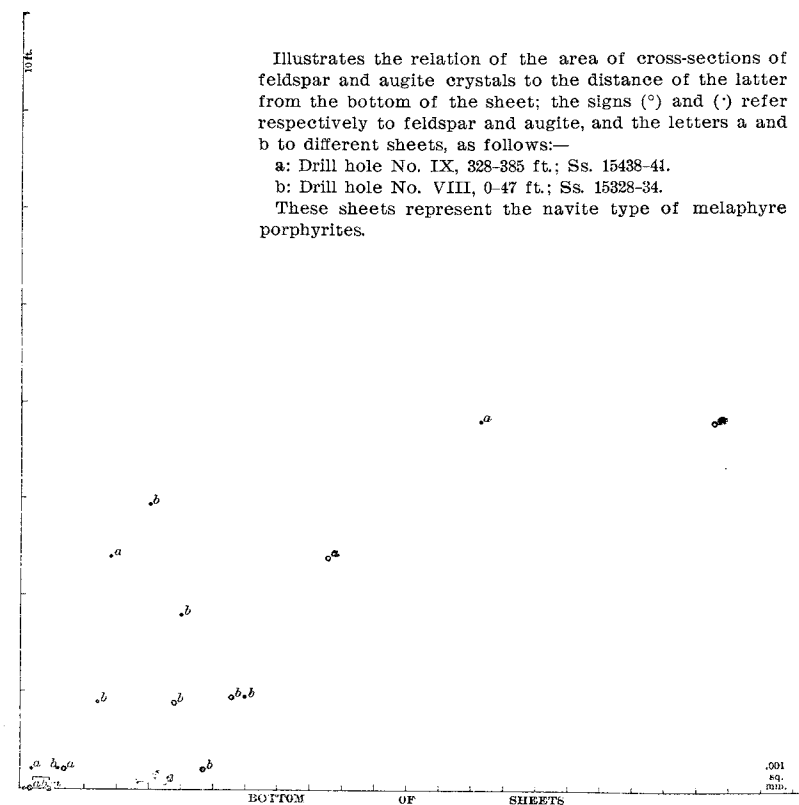


Fig. 19

Leaving the ophites, and coming to more feldspathic rocks, we have a number of types to distinguish, illustrated by figures.

(1) In the first type, Fig. 19, which is that of a navite, the melaphyre porphyrite or ashbed diabase of Pumpelly, a very large amount of feldspar was formed in the porphyritic stage. The augite is no longer so markedly coarser in grain than the feldspar, though it is practically impossible to separate the feldspar formed before the sheet came to rest from that formed later. The dimensions of the augite are much smaller than in the ophites, and smaller than the porphyritic feldspars. Both the porphyritic feldspars and the augite increase to a maximum, without any middle zone of even grain.

At the bottom of drill hole No. XIII are some beds which in some respects resemble the first type (for in them there are two

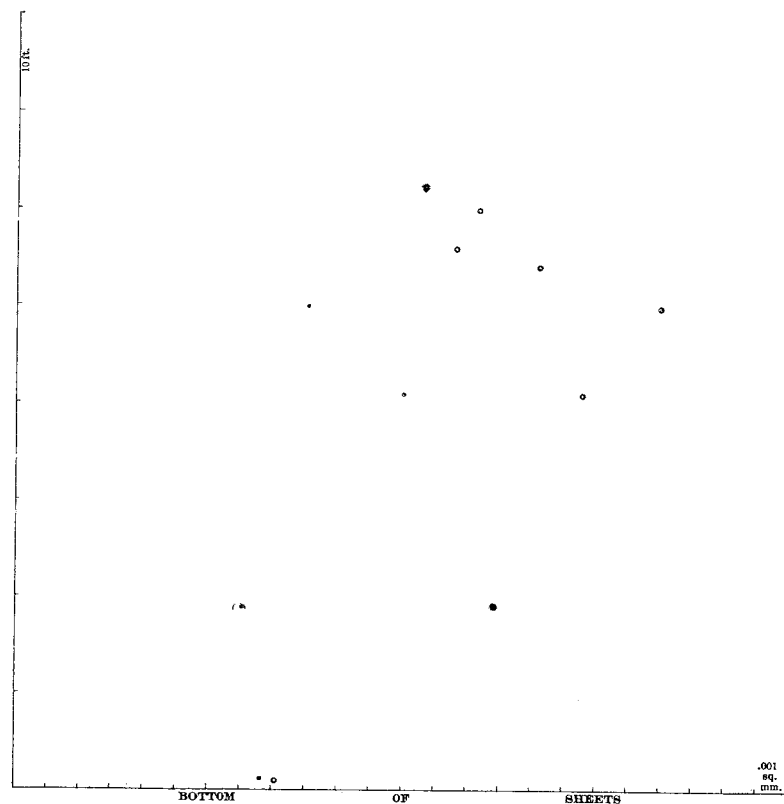


Fig. 20

Illustrates the relation of the area of cross-sections of feldspar and augite crystals to the distance of the latter from the bottom of the sheet, in the Huginnin porphyrite, Drill hole No. XIV, 367-436 ft.; Ss. 15814-19; the signs (°) and (•) refer respectively to the feldspar and augite.

ill-defined generations of feldspar), but are distinguished by a greater abundance of olivine and augite, and by the fact that both these latter show a tendency to occur in two generations. The bottom of these beds is not certainly known, and they are traversed by a fissure vein, but for the first fifteen feet from the top anyway, there is a distinct tendency in the various constituents to become coarser. It is like the previous groups in that the augite is, if anything, smaller than the feldspar.

(2) In the second type, Fig. 20, that of the Huginnin porphyrite, the augite is still more reduced in size, the amount of the feldspar being larger. The increase in size of grain from the margin is slight but perceptible, while the fineness of the grain exaggerates the errors due to imperfect averages.

There are very regularly porphyritic crystals, but they have nothing to do with those of the groundmass, being more than tenfold longer, much broader in proportion, and of a different chemical composition, whereas in the previous type the porphyritic crystals and those of the groundmass were inseparably linked together, grading into each other in size, while the average grain of both increases steadily toward the center.

The next diagram, Fig. 21, represents the grain for the two Minong beds combined, since the dividing line is not very certain. It will be noticed that the scale for the augite areas is to that of the feldspar as 1:10, so that in the coarsest part the augite is really a good deal larger than the feldspar, though by no means so much so as in the normal ophites, and the rock has a really ophitic texture. In the upper part of the flow this texture disappears. It will also be noticed that in the two holes where these beds were cut, they have the same degree of coarseness, so far as the augite is concerned, and the figures for the feldspar agree very well.

In the upper flow there is no certainly identifiable augite and the feldspar is practically uniform in size. The upper flow, as we have remarked, is more of a felsite, and the variation in grain is much less perceptible.

In the felsite at the very bottom of the column, there is some poikilitic quartz, which is probably secondary. The grain is otherwise very fine, and remains very fine for the eighty feet or so that this bed was penetrated.

§ 9. Summary.

Thus we finish the examination of the variation of grain with reference to rate of cooling. Gathering up what we have learned, we find:

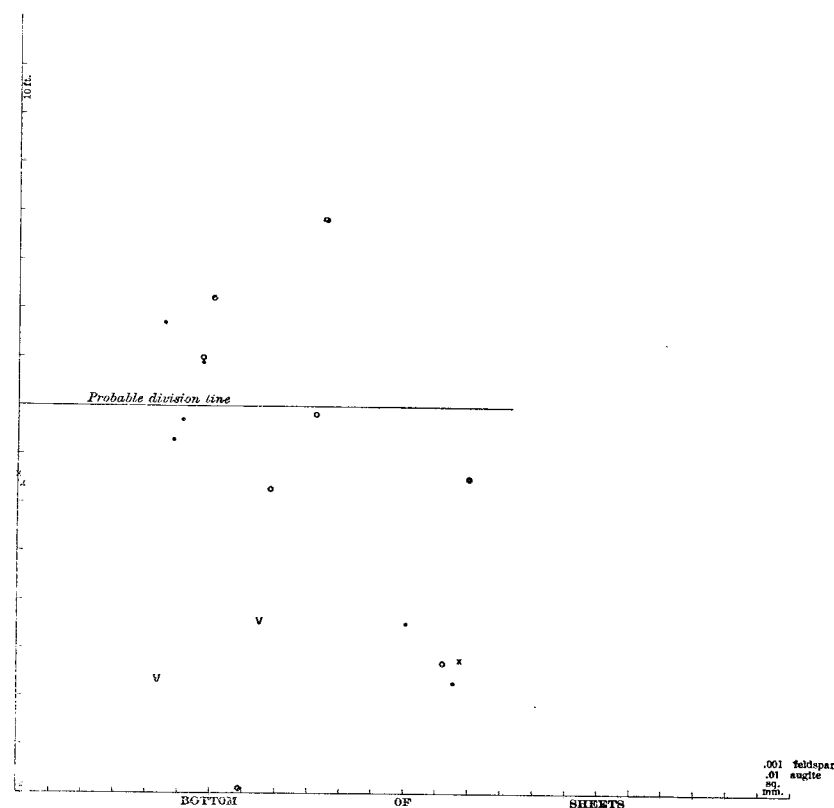


Fig. 21

Illustrates the relation of the area of cross-sections of feldspar and augite crystals to the distance of the latter from the bottom of the sheet, in the Minong trap and porphyrite; different signs indicate the various observations, as follows:—

- Feldspar, in Drill hole No. I, 426-536 ft.; Ss. 15044-54.
- v Augite, in the same flow.
- o Feldspar, in Drill hole No. III, 100-415 ft.; Ss. 15116-28.
- x Augite, in the same flow.

(1) The relation of grain to distance from margin, and its correspondence with the laws of cooling, are most conspicuous in the augite of the highly augitic rocks, and less marked in oligoclase and in the porphyrites.

(2) The flows of Isle Royale show a grain increasing markedly up to the very center of the sheets, as is to be expected in sheets

which stopped flowing only when near the temperature of consolidation.

(3) The relative grain of different minerals shows little or no connection with the distance from margin, nor with the laws of cooling.

(4) The effect of the laws of cooling cannot always be traced in the porphyritic crystals, but sometimes crystals, which began to form before the cessation of motion, continued at the center to grow uninterruptedly thereafter, so that while two generations can be distinguished at the margin only one can be observed at the center.

§ 10. Effect of chemical composition on grain.

The effects of chemical composition on grain have already been brought out incidentally in discussing the laws of cooling, for they appear as modifying these laws. Gathering these scattered observations together (p. 133 and the various diagrams), we have an almost self-evident law, to wit:

Other things being equal, the greater the abundance of its constituent molecules the coarser the grain of any mineral.

This may farther be illustrated in two ways:

(1.) In the case of a single flow like that from drill hole No. X, 338 feet to 415 feet (Ss. 15513 to 15524), we find a greater abundance of augite at the bottom of the bed. This is indicated by the analyses, by Mr. F. P. Burrall,* which may be separated with more or less probability into constituent molecules as I have done just be-

DR. L. L. HUBBARD,

State Geologist, Houghton, Michigan.

*MARCH 2, 1896.

DEAR SIR:—The specimens submitted to me for analysis during the month of February gave the following analyses:

	No. 15515.	No. 15519.	No. 15523.
SiO ₂	46.45	46.25	46.13
Al ₂ O ₃	16.60	18.39	19.79
Fe ₂ O ₃	2.72	7.70	7.24
FeO.....	7.25	3.52	3.79
+CaO.....	6.32	12.19	11.43
MgO.....	9.21	4.65	7.27
K ₂ O.....	1.02	1.04	0.52
Na ₂ O.....	4.05	3.76	2.55
CO ₂	0.40	1.00	0.29
H ₂ O.....	5.01	3.41	1.83
Totals.....	99.03	101.91	100.84

† In each case the MnO was weighed with CaO and not separated. In no case would MnO run over 0.1%. All three rocks melted over Bunsen blast lamp quite easily and formed a black glassy globule. They all seemed to melt with equal ease.

Very respectfully,

(Signed)

FREDERICK P. BURRALL

low. These considerations agree with direct observation of the thin sections in indicating an increase of augite as we approach the bottom of the bed. Now Fig. 22 shows that the grain of the augite in the lower and more augitic part of the flow is larger than would be expected under the laws of cooling and smaller in the upper part of the flow. We have called attention to a slight

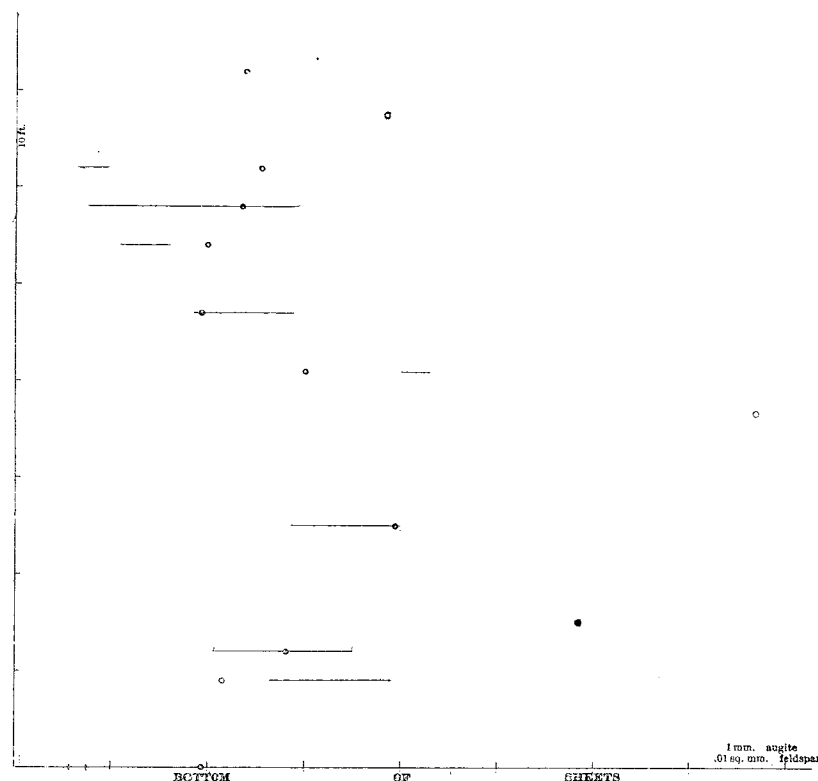


Fig. 22

Illustrates the relation of the area of cross-sections of feldspar (o) and augite-crystals to the distance of the latter from the bottom of the sheet, in the sheet that has been analyzed:—
S. 15523 at 9 ft., S. 15519 at 41 ft. and S. 15515 at 62 ft., respectively, from the bottom of Drill hole No. X, 338-415 ft.; Ss. 15513-24.

indication of the same thing in the Greenstone diagram, Fig. 14. It is obvious also, in the Minong trap, Fig. 21. But a general study of the thin sections indicates more distinctly than any diagrams that this tendency for a bed to be, *pari passu*, more augitic and coarser at the bottom than at the top, is very general.

Pumpelly's analyses of bed 87 (IX and X at the end of Chapter IX) indicate the same thing, though his specimens were much altered.

On pages 146 and 147, in dividing up the analyses of Nos. 15515 and 15523 into the probable constituent molecules of the original rocks, I have neglected the water and the CO_2 , as they can be easily accounted for afterwards by turning the molecules into their hydrated forms as they appear in serpentines, chlorite, etc. Of course such a division is ideal. The Fe and Mg replace each other in all the molecules in which they appear, but that makes no material difference in the relative proportions of the constituent minerals. It would only change them slightly in composition, the olivine being less ferruginous and the augite more so. Of more importance is the K_2O . It is uncertain whether originally it occurred in a feldspar molecule absorbing SiO_2 , or with part of the olivine molecule making biotite, as I have figured it, or entered, as is not at all impossible, into augite, or was in the residual glass, or irregularly divided among these various molecules. In any case it is likely to absorb an equal molecular proportion of Al_2O_3 . There will be a varying amount of SiO_2 thus used which will imply a correspondingly varying proportion of olivine and augite. A much greater cause of uncertainty is the iron, which is liable to have changed its state of oxidation, and may have occurred originally either in the augite, the olivine, or by itself, and leaves quite a chance for different interpretations, the only thing practically certain being that alkaline feldspar and the olivine decrease toward the bottom, while the augite increases.

(2.) The second application of this rule is to different flows. If we compare the dimensions of the augite in the Greenstone and its congeners as exhibited in Figs. 15 and 16, first with the grain of the augite in Ss. 15497-15501 (t in Fig. 16), then with the Minong trap, Fig. 21, and then with the porphyrites of Fig. 19, we see distinctly the lower gradient of increase of the augite in the less augitic rocks, the augite in the Minong trap being, relatively to position, about half the size of the Greenstone augite, that in the porphyrites nearer the thirtieth. Even in such a sheet as that from which come Ss. 15762-15772 (e), which is ophitic throughout, though recognized as less augitic than usual, the falling off in the gradient or rate of increase of grain is distinct. The numerical formula given on page 129