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LUCIUS L. HUBBARD, STATE GEOLOGIST

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GEOLOGICAL REPORT ON ISLE ROYALE MICHIGAN

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ACCOMPANIED BY SIXTEEN PLATES AND TWENTY-NINE FIGURES INCLUDING MAP IN COVER

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OFFICE OF THE STATE GEOLOGICAL SURVEY,
Houghton, Michigan, December 15, 1896.

To the Honorable, the Board of Geological Survey of Michigan:

GENTLEMEN—Herewith I transmit Reports, with maps and illustrations, covering work done by the State Geological Survey in the Upper Peninsula, principally during the years 1895 and 1896.

With great respect, I am your obedient servant,
LUCIUS L. HUBBARD,
State Geologist.

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CHAPTER I. HISTORICAL INTRODUCTION

§ 1. Prehistoric Mining.

The progress of knowledge is like the growth of a coral reef; each generation builds upon that which has been left behind by those who have gone before. It is, therefore, fit that this account of the geology of Isle Royale, a part of Michigan hitherto practically untouched by the State Geological Survey, should begin by a review of the records of what others* have in the past done toward its geological development.

*Jackson, Executive Documents, No. 1, 1849, First Session, Thirty-first Congress, p. 371. Hereafter cited as "J."

Foster and Whitney, Report on the Geology and Topography of a portion of the Lake Superior Land District in the State of Michigan, 1st Sess. 31st Con., Ex. Doc. No. 69, 1850, Pt. I, p. 162. Hereafter cited as "F. & W."

Gillman, Henry, "Ancient Works at Isle Royale, Michigan." Appleton's Journal, Aug.9th, 1873, X, p. 173, "Mound-Builders and Platycnemism in Michigan." Smithsonian Report, 1873-74, p. 364, 1st Sess. 43rd Con. " The Ancient Man of the Great Lakes," Proceedings of American Association for Advancement of Science, 1875, B., p. 316-330.

Winchell, N. H., 9th Annual Report Minn. Geological Survey, 1880, p. 162; 10th Annual Report Minn. Geological Survey, 1881, pp. 48-54; 14th Annual Report Minn. Geological Survey, 1885, p. 322; Popular Science Monthly, Sept., 1881, XIX, V, p. 601.

Swineford, A. P., Annual Report of Commissioner of Mineral Statistics, Michigan, 1884, p. 8.

Sherzer, Will H., "Platycnemic Man in New York," Report of State Geologist, New York, 1894, p. 663.

The first mining upon Isle Royale was long before the arrival of the white man. Like other parts of the copper region about Lake Superior, Isle Royale was visited by tribes contemporary with the mound builders, and sheets of native copper were worried out of the rocks in which they were found enclosed. The hammers used in this work were hard pebbles. Specimens of these hammers found upon Isle Royale were not grooved for a withe, which might be twisted around them for a handle. In this respect they differ from those found on the south shore of Lake Superior. Such is the testimony of W. W. Stockly, Jacob Houghton, Dr. Simonson, Capt. Wm. Uren, B. Livermore, S. W. Hill and others, who have spent much time on the island, and their statements are confirmed by my own observation, as far as it goes. Winchell, however, says that occasionally and exceptionally one is found grooved, and figures one found on Isle Royale which belonged to Dr. Galley. On Isle Royale they must certainly have been most exceptional. Swineford also mentions grooved hammers from Isle Royale.

It is probable, from the abundance of charcoal and half burned sticks that were found near the "Indian pits," that fire setting was practiced by these miners, that is that the rock adjacent to the copper was caused to crumble by dashing cold water on it suddenly, after having heated it very hot. It was then shoveled away or farther pounded with the stone mauls above spoken of. Then the copper in its turn was pounded off and fashioned into various instruments, axes, knives, arrow- and spear-heads, etc. These early workings were exceptionally abundant about the Minong mine and will be farther referred to when we come to the history of that mine (§ 3), but they also occur at the extreme northeast of the island on Blake Point,* and on a little island off Washington Island at the extreme southwest end of the Isle Royale archipelago, for the main island is fringed with more than a hundred and fifty smaller islets, and innumerable minor rocks.

These workings are prehistoric. By this we mean, that while they may well have been contemporary with Greek or Asiatic civilization, they were not being worked by the aborigines when the first hardy Jesuit missionaries penetrated into these regions, but were then already covered with a growth of forest.† Gillman thinks that they may have been abandoned seven or eight hundred years ago, judging from the size of the stumps of decayed trees. The works, however, were, as Winchell says, later than the glacial period, and later than the period of lakes much larger than the present, that immediately followed it, as they come down to within thirty feet of the present water's edge, or, according to Gillman, to within less than eighteen feet of it. Now Isle Royale, from one end to the other, shows evidence of a recent emergence from Lake Superior. This evidence consists in raised beaches, over which barely more than lichens have grown, in cascades falling into the lake, and in other marks. Hence no very great age can be assigned to the end of these workings. Winchell thinks that the miners and mound builders were the aborigines found here by the first discoverers, in other words, the Indians, and quotes a large number of references to the possession of copper by the Indians, and their use of it and knowledge where it occurred. So, also, Foster and Whitney quote from Father Dablon, in a "Relation" for 1669-1670, an account of "Menong," celebrated for its copper, and there is also an account of gathering copper there. Pierre Boucher in 1640 speaks of a mine of copper on an island in Lake Superior (Swineford, *loc. cit.*, p. 8). If we agree with Winchell that the miners were the Indians, we must suppose that the contact with European civilization, and the introduction of iron, made the early and laborious copper mining unprofitable, and that these early copper mines shut clown for the same economic reasons which shut down mines at present. A very curious fact is reported, that none of the bones of the ancient miners have been found (Swineford, *loc. cit*., p. 9), though the fish scales of their noonday lunches, their wooden bowls and implements, and even a bit of knotted rawhide have been preserved. Can we imagine that mining of copper was a prerogative of some class of medicine men who visited the island only at intervals? The possession of copper implements must have been at one time a coveted privilege. The question of the true nature of the earliest copper miners is, however, only a branch of the general question as to the character of the mound builders, which is likely to be settled by researches elsewhere, and is complicated with various considerations, as to the racial value of platycnemism, etc., that would carry us too far from our subject. Therefore, leaving the above references with those who desire to pursue the subject farther, we pass on to the historic epoch.

*F. and W., l. c., p. 162.

†Henry Gillman, Smithsonian Report, 1873-1874, p. 386.

§ 2. Earliest Historic Explorations, 1844-1855.

With the ending of the copper mining just described Isle Royale seems to have been abandoned, except by occasional trappers and fishermen,* though some report of its mineral wealth is said to have reached Franklin, perhaps through the Jesuit "Relations" and through his French friends, and to have led him in making the treaty with Great Britain which defined the limits of the United States, to curve the boundary line slightly so as to take Isle Royale and separate it from the Canadian shore, nearest to which it lies. The earliest explorations for copper were on the other side of the lake, and I have no record of mining or geological exploration on the island until after its cession with other lands, by the Chippewas in 1843.** Soon after this, prospectors appeared on the island, among them, in 1845, the veteran geologist, James Hall, who gave Chippewa Harbor its name and who was nearly caught on the island by the approach of winter, and crossed the lake in a small, open boat.† In 1846 explorations began and by 1847 the island presented perhaps as lively a scene as ever in its history. The U. S. Linear Survey was being pushed by William Ives and his assistants. I cannot let Ives's name go by without especial note as to the fine character of the work he did. Working far from civilization, through an extremely rough and densely wooded country, with an enormous amount of lake meandering, as will be obvious from the map, he turned out work far surpassing that customary on the Linear Survey, which has never been properly appreciated because never properly worked up, the map in this report being the first in which his notes have been computed and platted. This map is the work of Mr. W. W. Stockly. In the same year the U. S. Geological Surveyor, C. T. Jackson, made his first visit to the island with Messrs. Ransom, Peabody, Foster, etc. The margin of the island was then dotted with explorations, which within ten years were all closed. Let us review them briefly, beginning at the southwest end of the island.

*The Hudson's Bay Co. had a station on the island, Sec. 24, T. 64, R. 37, and the American Fur Co. one at Sec. 35, T. 64, R, 37; (J. 427), and near Card Point and perhaps on Fish sland, Sec. 35, T. 66, R. 34; Hulbert's map.

**F. and W., p. 15, and J., p. 1157.

†Private communication.

On Washington Island (referred to by Foster and Whitney and others, as Phelps Island), the Ohio and Dead River Company had Isaac Hewitt and Mr. Wright, an English miner, at work (J., p. 426) on three veins of only an inch wide, composed of datolite, compact feldspar and prehnite, containing a little native copper. Strike N. 17° E.; dip 75° W. Compare Jackson's map. These were on the north side. By the next year, when Dickenson and McIntyre visited the region, the place seems to have been abandoned (J., p. 506). Foster and Whitney (F. & W., p. 91) also mention veins on the southeast shore (Sec. 10, T. 63, B. 39) containing calcite, prehnite and native copper, and striking S. S. E., 18 inches wide. Farther east was another vein of great power, 30 inches wide and striking nearly north (dip 78° X. ? J., p. 770), with quartz, laumonite and prehnite, and disseminated copper, and on the S. E. ¼ of the same section another copper-bearing vein well defined, 7 inches wide.

At Huginnin (J., text, p. 425, Huganon; map, Huganin; F. and W., p. 90, Hugennin) Cove, Sec. 19, T. 64, R. 38, was an exploration of the Isle Royale and Chicago Company, soon abandoned.

Farther along the shore in Sec. 11, of the same township, was the Franklin Company (J. B. Corey, agent), working on some small veins of copper, striking north, and two of them 4 to 6 inches wide. These were also soon abandoned (J., p. 425).

On Sec. 33, T. 65, B. 37, the Siskowit Company had a location in charge of Chas. Whittlesey, the same who had charge of the Siskowit mine.* This was on some small veins and soon abandoned (J., p. 425). Passing over the veins near by, described by Jackson (p. 425), which do not seem to have been worked upon, we come to the Pittsburg and Isle Royale Company's location at Todd Harbor. This was one of the most important openings of the time, and was still worked when Koch visited it in August, 1850, and the traces of the old workings were still very plain when I visited the region in 1893. Foster (J., p. 770) also speaks of McCullough's working at the outer point of Todd Harbor. The works lie near the harbor and are in and near the lower side of that group of rocks that I propose to call the Minong trap, since it underlies the Minong mine, later to be described (p. 16). These rocks are more acid, as is shown by the less development of augite, than the flows above and below (see Chap. III), and answer well to Foster and Whitney's description of "hard greenstone with a conchoidal fracture," the clean fracture being especially characteristic at the bottom. The main location was on

Sec. 12, T. 65, R. 36 (F. and W., p. 150). The first working that Jackson examined (J., p. 424) was a stockwerk without any well defined walls, thus resembling the occurrence at the Minong mine. The veinstone he says was an amygdaloid containing laumonite, calcite, datolite, and native copper, the metal occurring in pieces of a pound weight. This copper-bearing rock was 15 feet wide and in general sloped to the north.

*See below.

Another vein was 7 to 8 inches wide; strike N. E. and dip to N. W. 65°. In a third place was a vein a foot wide, bearing thin sheets of copper. Strike N. 25° E., dip to N. W. 74°. As is often the case, the wall rock "is shivered into a shingle of slaty appearance, and is disintegrated for the width of four or five feet." This last vein is probably also given by Foster and Whitney as the lode with a strike N. 20° E., dip W. 78° (p. 150). Foster and Whitney also seem to allude, on pages 150 and 169, to another vein running north and dipping to the east. They describe two shafts, 63 and 67 feet deep, with the first adit or level 42 feet long, the second 113 feet, the third 18 feet, fifty tons of ten per cent ore raised, and twenty-four men employed. In the following summer, July, 1848, the mine was again visited by Dr. Jackson's agents, who in substance reported (J., pp. 505, 509): There were then nine men employed. Three veins were worked, two a short distance from the one (!) worked last season. After drifting on that vein some 30 feet the copper disappeared. A shaft was then sunk a short distance north of this drift, and in sinking 5 or 6 feet, a blue earth was struck filled with copper in the form of shot. This bed was 5 to 6 feet thick and below this there was a red colored rock filled with spar, but it contained no copper. Then they drifted 60 feet from the edge of the lake on a vein 2½ feet wide, with well defined walls dipping W. 70°. One sheet of copper was exposed, 8 feet long, 4 feet high and 1 to 2 inches thick.

West of this vein (No. 3) a shaft was being sunk on a small spar vein with some copper. There was still another vein east of the agent's house, which ran north (No. 4). The agent sank a shaft on this vein so near the lake that the water compelled him to abandon it, and then he went farther inland and sank a shaft, and also struck a small spar vein running east. James McIntyre (J., p. 509) gives vein No. 3 as striking N. N.E., dipping 70° W., and mentions that they are sinking a shaft from the top of the hill to strike the drift.

In August, 1850, the island was visited by the German mining engineer, Fr. C. L. Koch, who found only the Todd Harbor and the Siskowit works still in operation. He gave to the world the observations that he made on his trip, in Vol. VI, parts 1 and 2, of the "Studien des Goettingischen Vereins Bergmænnischer Freunde," 1852, and I will translate from this rare report that part which refers to Isle Royale. The map accompanying is a copy of that of Foster and Whitney, with the original misprints retained, and others added (Amyghaloid Island for Amygdaloid Island, Loke's Point for Locke's Point, etc.).

“Todd's Harbor,* Pittsburg and Isle Royale Company, on the northerly shore of the island, opposite Canada. The company has undertaken several exploratory openings here, of which one was in operation when I was there (1850), close to the lake, probably only 20 feet above the surface of Lake Superior. The wall rock consists of a close grained, crystalline, dark amygdaloid, which may be considered as a transition to a close grained or compact trap. The vein stands in this, striking from south to north, and as it appears, dips tolerably vertical. So far as the vein is yet known, it is not very wide. The vein-rock is here a compact chloritic mass, with quartz, calcite, and prehnite, which minerals occur in small druses with a tendency to crystalline form and also as complete and beautiful crystals. Beside these I also noticed associated with calcite the reddish yellow feldspathic mineral, and small but very beautiful apophyllite crystals. I also found small copper crystals here.

"The product of good stamp copper appeared to be not inconsiderable and will be made manifest as soon as the stamp mill begins work, which is in process of construction (which will take its water for motive purposes [?] or for jigs, ["Aufschlagwasser,"] from a little stream which forms a beautiful waterfall on the margin of the lake near the mine). Some barrels of the coarser masses of copper, some of them weighing several pounds apiece, were packed for shipment. The mine was manned with only a small force, and it was uncertain whether the vein was to be explored to a greater depth. It would be regrettable if the company should withdraw their capital from this locality; it deserves, at any rate, a still closer investigation.” Page 201, trap contains augite and labradorite; p. 202, epidote replaces the augite and quartz the feldspar; p. 205, copper; p. 213, apophyllite at Todd Harbor (with copper crystals and prehnite); p. 217, prehnite at Todd Harbor; p. 210, epidote (thallite).

*Pp. 188, 189.

The first shaft that I saw on my visit in 1893 was nearly vertical and 30 to 40 feet deep. It was in a light green seam with a little copper in a compact, slightly mottled trap. About 100 feet north-east the openings on vein No. 3 are well marked; strike S. 25° E., dip 75° W.; and at the water's edge there is an adit connected with the opening. This seam, and joints parallel to it, intersect a laumonite seam which is nearly parallel to the formation (strike N. 50° E., dip 54° to S.E.), without displacing it. The seam is about 300 feet from the ten foot fall mentioned by Koch, which does not come in at the lowest point of the shore, and is a significant index of the recent changes of lake level.

Continuing northeast, the next location visited by Jackson (p. 424) was that of Mathewson Miller, (J., p. 770) or, as Ives called it in his field notes, the Amygdaloid and Isle Royale Mining Company, Sec. 23,

T. 66, R. 35, where the main vein had a strike to east, dip to north, was 2 feet wide, and had yielded about 30 pounds of copper. Another vein near by had a strike N. 60° E.; dip to north. This is opposite Hawk Island, and just north of the Minong mine.

On Amygdaloid Island (J., p. 423), claimed by Miller and the American Exploring Company, was a vein of little value, dip 48° to N. by E.—epidote with a little copper. Neither of these locations is again mentioned.

Of Duncan's explorations, on Secs. 27, 28, 33 and 34 of T. 67, R. 33, on Duncan Bay, about three-quarters of a mile from Monument Rock, nothing more is written (J., p. 423), unless Foster and Whitney, in their reference to the Duncan vein on Sec. 34, T. 66, R. 34, have made a slip and really refer, as I am inclined to suspect, to T. 67, R. 33 (E. and W., p. 169). They were doubtless soon given up.

Coming to Scovill Point, we find once more comparatively siliceous traps, having passed around Blake Point, which marks one end of the great range of basic lustre-mottled melaphyres, or as Footer and Whitney call them, varioloid greenstones, which form the "backbone" of the island. The more acid beds lying above correspond to those lying around the "Ashbed" on Keweenaw Point, as will be later shown, and like them are much more inclined to a fine grained texture, with basaltic jointing, and a cleaner conchoidal fracture, as mentioned by Foster and Whitney (p. 82-83). Here, on the "forefinger" (J., p. 770) of the island, Scovill Point, Jackson found Scovill (J., pp. 422, 423, 505; F. & W., pp. 83, 169, 171; both spell the name without the final e) on Sec. 35, T. 67, R. 33. The vein on which he was working was from 1 foot 3 inches to 2 feet 6 inches wide, with some lateral string veins or leaders, containing a greenish mixture of calcite, prehnite and trap, and sheets and spicules of native copper. The strike was N. 65° E., dip 68° to N. W. (J., p. 422). By the next year, when Dickenson visited it, there was but one man left, and but little had been done in the interval. Only a shallow pit was opened. A marked ravine and "fossa" are said to indicate a continuation of this vein to the southwest, according to Foster and Whitney, nearly nine miles. This may possibly be so, but the strike of the vein as given is nearly that of the formation, which dips off to the southeast at an angle of about 17°, and from my observations I should say that Scovill Point was made up of two flows of trap (J., p. 770) and that the hollow, running as Jackson says, by solar compass N. 61½° E., var. 6½° E., marked the line of contact of the two beds with associated amygdaloids.

Shaw's or Smith wick's location, the next met, was on Sec. 4 and perhaps also Sec. 3, T. 66, R. 33, directly opposite to Smithwick's Channel, about 100 rods southwest of Scovill's, along the line or vein mentioned above. The deposit there was similar to Scovill's, and contained some specks of silver. In 1848 there were three men there and the shaft was down 90 feet (J., pp. 422, 505). By 1849 (J., p. 605; F. and W., p. 171) it was down 96 feet. For 30 feet the rock was soft, the vein well developed, expanding in places to 4 feet in width, and containing considerable copper. Then a band of columnar trap was struck and penetrated 66 feet. The vein contracted to a foot in width and wais nearly worthless. This columnar trap appears, according to Foster, in the point north of Scovill Point, at the water's edge, and continues in a cliff on the north side of the point, 30 to 40 feet high (J., p. 770). Mr. Shaw (F. and W., p. 171) had a similar experience on the main point, Sec. 33, T. 67, R. 33, where he sank 15 feet on a vein composed of quartz, chlorite and calcite with considerable copper (strike N. 50° E.), where on passing from a crystalline trap with feldspar to a darker trap, the vein became worthless.

On Mott Island, Jackson (J., p. 422) saw a small copper vein, 4 inches wide; strike N., 80° E., dip 50° to N. The veinstone is 2 feet 4 inches wide, but is not all metalliferous.

The next location was, we believe, the most enduring of any of those worked in 1847, as well as one of the first opened. Called by Jackson the Union Company, its permanent name was the Siskowit mine. Chas. Whittlesey, a cousin of the prominent writer, Col. Chas. Whittlesey, of Wisconsin, came up in the Julia Palmer (the first steamer on Lake Superior) in October, 1847 (with Mr. John Senter), to take charge of the explorations, and wintered there. Under him was Mr. Jas. Hubbard. The explorations were on Sec. 13, T. 66, R, 34. The vein Jackson (J., p. 421) found to be 5 feet wide, the copper mainly in sheets in contact with the walls of the vein, which is well defined. Veinstone (F. and W., p. 150) was epidote, chlorite and calcite, with copper disseminated and in sheets and masses,—the largest mass (F. and W., p. 143) 350 pounds; strike, N. 88½° W., dip N. 82°, or, according to Foster and Whitney, 75°. Jackson also noticed (J., p. 421) three small veins which traversed these rocks. Next year Dickenson found a 40 foot shaft, and a 90 foot drift, with about 40 tons of ore (J., p. 505). In 1849, Foster and Whitney reported two shafts, respectively 40 feet and 35 feet deep, and 115 feet of drifting. As at Shaw's location, just described, 35 feet to 40 feet below the surface the vein passed from an overlying amygdaloidal trap (F. & W., p. 171; p. 150, dark, compact trap) to a columnar bed in which the vein was badly pinched. In August, 1850, Koch visited the mine, and we translate his description:—(*loc. cit.*, p. 185.)

"1. Siskawit Mining Company, Town 66, Range 34, Sec. 13, situated on the south [*sic*] shore of Rock Harbor. The principal strike of the trap ridges of the island is from south-west to north-east. The deposit worked by this company strikes from east to west and dips about 35° to the N. E. It crosses the trap rock, therefore, at an angle of about 45°. The principal rock in which the copper occurs is of a chloritic nature, more or less solid, possibly as there is more or less siliceous matter mixed with it; it assumes an amygdaloidal character near the country rock and finally passes into an amygdaloid, which has, however, a tufaceous ["blattersteinartiges"] appearance, owing to various kinds of crystalline secretions, especially of calcite. I have not been able to perceive distinct selvages, but at many points one can distinguish the chloritic rock-mass from the country rock. This copper lode is about 2½ feet thick, but the copper has penetrated into the foot- and hanging-wall beyond and outside of it. At many points the copper occurs in thin plates, which now and then thicken to larger pieces, up to several pounds in weight. It occurs less often in thick lumps. Not rarely we find in the chloritic mass small druses with crystalline copper, transparent colorless ["hellen weissen"] calcite crystals, and other small crystals of a feldspathic mineral of yellowish and reddish yellow color. Whether another mineral which occurs in indistinct crystals belongs to the zeolite family (perhaps analcite) I shall not venture to decide.

"Since the mine furnishes principally stamp rock, the steam engine just put in place, by which the stamp mill, etc., are to be run, will meet one of the most pressing needs. Considerable of the coarser masses of copper had already been sold, and they figure on a product of about 30 tons up to the close of navigation. The elevation of the point where the mining is at present being pushed, above the lake level, is inconsiderable, perhaps only 30 or 40 feet; if one does not shortly have to fight too much with water, this field may perhaps give favorable results. At that time ten miners were employed, and thirty odd people in surface work."

The deposit seen by Koch seems to have been different from that visited by Foster and Whitney. The former is possibly the one mentioned by Foster and Whitney as 1,800 feet west of Shaft No. 2.

The Siskowit mine continued working until 1855. Capt. W. Tonkin, later of the Atlantic mine, was in charge from 1852 to 1853. He reported to Swineford (p. 10; the account below is based also on personal interviews with Capt. Tonkin and John Senter) that the work was done on two veins, the more easterly of which dipped to the west, thus corresponding to the one above described by Jackson and Foster and Whitney, and at the time Capt. Tonkin left, the shaft upon it was down to the sixth level. Afterward this shaft was sunk 100 feet more, to about 500 feet in all, but the vein was lost. The other, or west vein, was very nearly vertical and the shaft upon it was down to the third level. The mine produced about 150 tons of copper. Each vein carried some copper, and it was Tonkin's expectation that when they came together, as he expected them to do at about 600 feet, a good mine would be found. That depth was never attained. The white chimney of the old mine is still a conspicuous feature of Rock Harbor. My notes of the mine are as follows: The old dump extends to the water's edge; specimen No. 16282 represents the country rock trap, at the surface, while specimen No. 16283, from the dump, doubtless represents the columnar trap spoken of, being fine grained and black. About 100 feet . northwest from the shore is the old stack, and immediately adjacent, the foundations of two old buildings are visible. Directly from these to the west are four old test-pits or shafts, extending for 400 feet or more, filled with water, on a vein striking north of east and dipping to the north 73°. About 150 feet farther northwest is another row of five or more pits on a vein apparently parallel to the last mentioned (strike 3 N. 80° E.), and dipping perhaps very slightly to the north. It is obvious that, taking the dips as 90° and 75° (F. and W., p. 150), and the distance between the two veins as 100 feet, we get just the 600 feet which Tonkin spoke of as the distance at which they should meet. The trap ledges seemed to strike R. 49° E., and to dip 17° to the southeast. The elevation of the work was about 25 feet above the lake (see cross-section E-F, Pl. XIII).

On the next section adjacent, to the southwest (Sec. 23), were explorations of the Ohio and Isle Royale Company which seem to have been confused with those of the Siskowit mine just described (Swineford, p. 10; F. and W., pp. 143, 144, 150; J., pp. 418, 419, 505, 796). It is obvious from these references that Swineford is in error in saying that Foster and Whitney's report does not mention the Pittsburg and Isle Royale Company, nor the Siskowit Mining Company. It appears also that C. C. Douglass was the agent for the Ohio and Isle Royale Company, which had very numerous explorations in various parts of the island, and was distinct from the Union Company, afterward Siskowit Mining Company, which had Whittlesey as agent. The description of the location of the first explorations as one mile northeast of the main entrance to Rock Harbor, fits the Ohio and Isle Royale, but hardly the Siskowit mine. Swineford's doubt as to the furnace is also clearly unjustified, and he is also in error in saying that Foster and Whitney make no reference to the ancient diggings (F. and W., p. 162).

The rock is reported like that at the Siskowit mine and on the S. E. ¼ of Sec. 22, at 20 feet they struck the columnar trap again, the vein pinching from 3 feet to a mere seam, and it seems to have been taken as the same vein, which, considering the strike, it could hardly be, though very likely of the same system of veins.

Other similar openings were made by this company, on Sec. 23 and Sec. 27 adjacent, T. 66, R. 34 (F. and W., pp. 144, 171), and the latter section was the site of the town of Ransom, opened by Ransom and Reynolds in 1846, where quite a clearing was made. It is at the mouth of the stream draining Lake Benson. The explorations here were similar to those at the Siskowit mine, etc. (F. and W., p. 144). In 1847 the company had fifty men at work. After the preliminary work by Leander Ransom, in 1846, J. H. Blake seems to have had charge in 1847. During a large part of the summer of 1848, Mark Matthews, now (February, 1896) residing in Houghton, had charge, but he left the same summer, and soon afterward C. C. Douglass arrived with workmen to finish the copper furnace (priv. comm.; J., p. 505; F. and W., p. 144; Koch, p. 187).

In 1849, Messrs. Douglass, Whittlesey and Shaw were still at work in these regions (J., p. 506), but, as we have already remarked, in 1850 Koch found only the Siskowit mine still manned.

Other explorations of the Ohio and Isle Royale Company were on Sec. 34, or Sec. 35, T. 66, R. 34 (J., p. 428; F. and W., pp. 143, 144, 150, 169; priv. comm. of Mark Matthews, and personal observations). There are some puzzling misprints in Foster and Whitney about what I suppose to be this location. On page 143 they give quite a description of a vein on the S. E. ¼ of Sec. 34, T. 66, R. 34, which they say is about two miles south of Rock Harbor by the lake shore, so that an adit has been started near the water level to intersect a shaft 25 feet deep, a short distance from the shore. The same description, is given on page 150, and again on page 169, where the vein is called the Duncan vein. This last name might lead us to think of the section whereon Monument Rock stands, the scene of Duncan's labors, but if so, both the town and range are wrong, and, besides, we have no other indication that the Ohio and Isle Royale worked in that neighborhood; nor is a mine indicated there on any of the maps.

On the other hand, if the town and range are right, the S. E. ¼ of Sec. 34 is more than a third of a mile from the lake in any direction and more than 25 feet above the lake, and has also no indication on the map of having been mined. (Jackson, to be sure, mentions, on p. 428, a vein at Conglomerate Bay, strike E. N.E., dip 85° to N., which might be in Sec. 34.) On Sec. 35, which is just adjacent, Foster and Whitney on their map indicate, by a sign which they use elsewhere only for the other two properties given in their table on page 150, a mine in operation, and Mr. Matthews remembers working in that region. Finally, on lot 5, of Sec. 35, I found traces of works corresponding to Foster and Whitney's descriptions (Sp. 16318, 16319). There are on this lot a number of ruined shanties and remains of a shaft house in a little cove. Judging from the shaft, the vein might have had a strike of N. 65° E. and a dip of 57° to N. W. There seem to be rhombohedra of dolomite in the vein rock and cavities coated with prehnite on epidote. These works are not very far south of some old works on lot 4, that I suppose to represent the Saginaw mine (but C. LeSage, a boatman who has been off and on the island for many years, said the more southerly work was the younger), which was developed much later in the seventies, in similar rock. Foster and Whitney give strike N. E., dip to N. W. 68°, the country rock a dark gray granular trap capped with greenstone, the length of the adit 40 feet, and the product 10 tons of 9 per cent "ore."

On Sec. 2, T. 65, R. 34, near Lea Cove (J., p. 504) or Lucky Bay (Winchell, *loc. cit*., 1881, p. 53) a shaft was sunk 40 feet (F. and W., p. 144). At the depth of 10 feet a belt of sandstone was struck which continued as far as the shaft was prosecuted.

On section 35, in the same town and range, another shaft is reported (F. and W., p. 144), 90 feet deep on a vein inclined to the northwest, the formation dipping to the southeast. But this location would be away out in Lake Superior! Should not the reference be to Sec. 35, immediately abutting on Sec. 2, on the north, *i. e.*, in T. 66, and thus to the works already described?

On Sec. 10, T. 65, R. 34, close to the line between sections 9 and 10, where a little pond on Sec. 9 is almost immediately adjacent to the lake shore, are the works known as Epidote, which I have visited (F. and W., pp. 144, 169; J., pp. 418, 770).

This Jackson describes as five miles southwest of Rock Harbor in latitude 48° 2' 8" N. "The whole coast is composed of trap rocks, with two beds of epidote rock, the upper of which is full of native copper. The copper-bearing bed is about one foot in thickness, and consists of a yellowish green, granular epidote, filled with angular grains of pure metallic copper very uniformly distributed, and constituting from 8 per cent to 20 per cent of its weight. Under the copper-bearing bed there is another bed of epidote, more compact in structure, and about five or six feet in thickness. This bed contains stellated masses of a mineral which I named chlorastrolite." The lower bed of epidote was hard to drill. The dip of the copper- bearing bed was S. E. by S., 28°. Small true veins of datolite, calcite and prehnite, containing spicules and sheets of copper, were seen to traverse the trap rocks and cut through the epidote veins. (Dip 60° to N. W. by W.) Foster and Whitney allude to the deposit at Epidote as a bed.

The works are, of course, much overgrown and obscured now. Their location is shown on the map. The elevation is about 50 feet above the lake, and less. The material of the dumps—there are three distinct pits noticeable—is sandstone, often indurated and full of epidote and calcite. It is highly probable that the works are in the same belt of sandstone which was met in Sec. 2, and which also outcrops at Chippewa Harbor from beneath the outer wall of trap. The epidotic zone is its upper contact, where it has been altered through the influence of the overlying traps, as it is for about three feet below the traps at Chippewa Harbor.

The work at Epidote was done in 1846-8. The next location was called Datolite (J., pp. 427, 505; F. and W., p. 88), on Sec. 34, T. 65, R. 35, and was named from the abundance of datolite found there. There were two veins, (1) 2 feet wide, strike N. 60° E., dip 50° to N. W.; (2) a few inches wide, strike N. 35° E., dip to N. W. Native copper in rhombic dodecahedra occurred in them. The Ohio and Isle Royale Company were sinking a shaft in 1848, while the work begun in 1846 had been allowed to lapse in 1847. It is possible that the descriptions of F. & W., pp. 143-144, may refer to this, as they fit pretty well, instead of to Sec. 35 of the township next northeast.

§ 3. The Minong, Island and Saginaw Mines, 1871-1883.

We have thus been around the island and described the numerous openings which marked the period of activity which culminated in 1847-48, and rapidly waned until the closing of the Siskowit mine in 1855. Then the island was a desert once more, with no permanent inhabitants. Thus it remained for many years, so far as any scientific results were concerned, though of course there were visitors. So for example, Prof. A. Litton, of St. Louis, informs me that the eminent geologist, D. D. Owen, with himself visited the island in 1858, on their return from the famous trip preparatory to Owen's report on the geology of Minnesota, Wisconsin and Iowa.

In the meantime, especially during the war period,* the property was gradually becoming consolidated, until the North American Mineral Land Company came to own most of the island north of the sandstone area.

*Swineford, loc. cit., p. 14.

The revival of activity on Isle Royale may perhaps be dated from the arrival of the engineers of the Lake Survey (John C. Mallory, G. A. Marr, etc.), who were employed making a chart and map from 1867 to 1871. At that time no mining work was going on.* But in 1871, when the U. S. Engineers were almost through, and only three men were left flashing signals from the station back of Rock Harbor, explorers for the North American Mineral Land Company arrived on the island, who were under the general direction of S. W. Hill, among them B. Livermore, yet alive, who had been with Whitney, and had helped him ascend Monument Rock in 1849 and 1850. The explorations of these parties which were carried on very extensively over the island, resulted in two promising mines.

In 1871, in the fall, the old Indian diggings on the Minong range were found, first on a fissure vein crossing the high outcrop of the Minong trap. In 1872, a force of forty men were set exploring, with the result, that there was disclosed an enormous amount of prehistoric raining on Sec. 26 and Sec. 27, T. 66, R. 35, between McCargoe Cove and Todd Harbor (Fig. 1.) Here the ungrooved cobbles that were used as hammers, could, it is said, be collected by the cartload. Some of the pits were 20 feet to 30 feet deep, and Capt. Uren tells me that in a stope 30 feet deep and 18 inches to 30 inches wide, boulders had been rolled in and wedged to take the place of timbering. There were drains for these pits, and in one case a drain 60 feet long had been covered by timber, felled and laid across.

As already mentioned, fire-setting had been employed, and a fragment of a wooden bowl about three feet across, and of a wooden shovel, and also of a rawhide string were discovered.

In May, 1873, the region was visited by Henry Gillman, whose account is referred to on page 2.

*Priv. comm. from J. C. Mallory.

In 1874 a company was duly organized to work these old mines once more, under the name of the Minong Mining Company (Minong being the Indian name generically for island and applied specifically to Isle Royale). An area of some 1,445 acres was bought from the parent North American Mineral Land Company, for the purpose, including in T. 66, R. 35, west of McCargoe Cove, the western half of Sections 23, 26 and 35, and the eastern half of sections 22, 27 and 34. In 1874 a mass of copper weighing 5,720 pounds.*

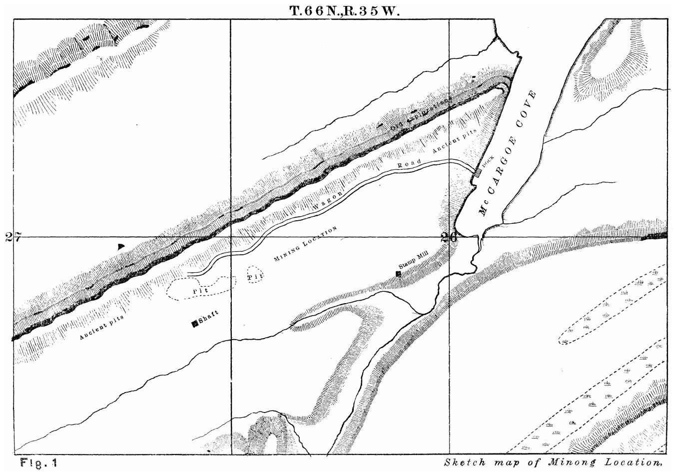


Figure 1. Sketch map of Minong Location.

In 1878 a mass weighing six tons was found, followed, in 1879, by two masses weighing respectively 3,317 and 4,175 pounds. The latter was about nine feet long. These large masses were buried, but there was a depression in the surface over them. In 1879 Winchell visited the island, and his published notes are found in the 10th Annual Report, Minnesota Geological Survey, and in the article above quoted in the Popular Science Monthly.

The first agent for the Minong Mining Company was A. Clayton Davis (Swineford says that he left at the end of the second year); H. Walker, of Detroit, President; E. W. Hudson, Secretary and Treasurer; Wm. Stevens, of Detroit, and John Senter, were prominent stockholders. Capt. Wm. Jacka was mining captain.

(*Winchell, Pop. Sci. Monthly, Sept., 1881, p. 602) which had been worked upon by the miners, was found on the island with poles underneath it, and was exhibited in Detroit and at the Centennial Exhibition of 1876, and afterwards sold.

Letter of S. W. Hill, Dec. 19, 1874:

"Commencing at the harbor in section 26, there is a ridge of bedded diorite having a direction south 60° west; its length in this property is something more than one mile. This ridge is traversed by veins, the greatest number of which bear south 10° to 30° west; there are more than twenty in this property, the greatest number of them have been extensively mined by a pre-historic race.

"The depth of some of these old mines has been found to be sixty feet; where the veins have been uncovered, the excavations in them by the old miners, when cleaned out they have been found well filled with copper; one thousand feet west of the harbor, in Sec. 26, west half, there is a group of several veins; the works of the old miners mark their course more than twelve hundred feet, the veins are united in the north part of the ridge. The evidences are that these mines will pay to mine. They are of good width; other and large veins near this group that have been extensively mined have been found.

"The Witthaus veins in the east half Sec. 27, form another group in which the works of the old miners are as extensive as even the works of this kind in both Minnesota and National mines, on the south side of the lake; these veins are large and well defined, and will, I believe, be found to be of great value when mined."

Letter of A. C. Davis:

"The property has a number of transverse veins that show a large amount of ancient mine work. I cleaned out one of the ancient pits on a vein near the east line of section 27. Its depth was twenty-six feet. I found a vein two feet wide. I put in a blast, and the result was about forty pounds of barrel copper, besides stamp work. I consider this vein a valuable one to mine for copper, and the chances of getting a paying mine I regard as almost certain.

"The property has a sedimentary belt running through it that is highly metalliferous. This belt has also been extensively mined by the ancient miners. I cleaned out three of the ancient pits on this belt, distant one from the other nearly a mile, in all of which I found barrel and stamp copper in quantity to warrant mining. At one point I made a cross cut across this belt, and found it to contain copper for a width of forty feet. It was in this cross cut I found the mass estimated to weigh 6,000 pounds. This mass had been detached from its bed by the ancient miner. I found a number of pieces of copper besides the mass, weighing from an ounce to seventeen pounds. I did not do any blasting in the cross cut, but broke the rock with a pick in many places, and invariably found it well filled with copper."

In 1876 a stamp mill was built, with a Ball's stamp, and is reported to have yielded, in 1876, 20.25 tons of "mineral" from 1,579.50 tons of rock, or about 1 per cent copper. A diamond drill was also employed.

In 1879 there was a reorganization, the Minong Copper Company replacing the Minong Mining Company. Dr. Simonson, at present of the Calumet and Hecla Mine, went there as physician. Among the later agents were S. Brady, and Capt. Hodgson. Finally, in 1883, the mining was suspended, but in the meantime from 1881 to 1883 the mine had been taken on tribute by John F. Johns, Cribeau and others, who worked a while longer and are said to have done pretty well the first summer, finding a six ton mass and a number of smaller masses, making about $800 to $900 apiece.* In the report of the Commissioner of Mineral Statistics, however, the mine disappears as a producer in 1883. The information as to tributing is from memory and therefore unreliable. The statistics of production are given in the table with the Island mine and the Saginaw, page 47.

The extensive location of the Minong is now all gone to wreck and ruin, and has been pretty thoroughly plundered. We find the traces of old explorations, whether prehistoric or not, clustered along the fine-grained trap, the same belt around which, McCulloch was working at Todd harbor. Here as there, too, the fine-grained black conchoidal trap is overlain by, and has apparently intrusive contact with a red, more acid rock (felsophyrite specimen No. 16,082 intrusive in 16,081 and 16,080A; Sp. 16,137-16,142, 16,155, illustrate the relations). Above this latter is a sedimentary bed of volcanic breccia.

*So I am informed by Godfrey Vaudrey, who worked in the mine from 1880 on, and now spends his summers on the island, fishing.

This same acid rock is, as we shall see later, exposed around Todd harbor but a little way south of here. The acid felsophyrite encloses fragments of the darker rock and is evidently affected in composition by it. Along this contact the copper occurs in a sort of stockwerk, that is, in a number of irregular and ill defined veins running into one another all ways, and the workings have followed them most irregularly. As usual in the Isle Royale ranges the south slope is the gentler, and all over this slope in Secs. 26 and 27, T. 66, R. 35, are found pits, and explorations, with a great many of the cobbles that have been used as hammers. The strike of the range from Todd harbor to McCargoe cove is about N. 61½° E., and the strike at the mine seems not far from 60°. The dip is about 20° to the south, and one shaft was put down following the dip and, probably in a general way, the contact of the intrusive rock. Some of Vaudrey's recollections of this shaft throw light on the general dip. According to him the diamond drill went down only 50 feet to 60 feet and got stuck, and they abandoned the bit. The drill hole was started about 200 feet from the dryhouse in lower ground, *i. e.*,southeast of it. The inclined shaft ran southeast under the dryhouse and would have struck the drill, it was supposed, within 500 to 600 feet. The shaft went down 300 feet; the ground was stoped from 100 to 300 feet. The slope of the shaft is about 1:4 and the shaft is not 100 feet from the surface at a point under the old blacksmith shop, so that the sound of the sledges could be distinctly heard in the dryhouse. It appears, therefore, that the dip of this shaft harmonizes pretty closely with the general dip of the formation and was following the upper side of the Minong trap, and its contact with the acid rock (felsophyrite). The intimate relations of this acid rock with the underlying trap, which is itself not as basic as are the beds in this part of the series commonly, are hard to describe. They suggest those red rocks which are often associated with basic rocks, apparently, as the result of chemical splitting in the original molten magma, such as Grant's augite granites,* some of the diorite porphyrites of Picnic Rocks near Presque Isle, etc. But in other places the acid rock seems more independent.

The mining began in an old Indian pit which was on a vein that crossed the bluff. From 1 foot the vein widened to 3 feet, when they had sunk 35 to 40 feet, and it contained a good deal of copper—a sheet 3 to 4 inches thick in the middle of the vein.

Beside the above explorations we find on the north side of the bluff a number of others, working along the lower contact of the trap or in the softer underlying amygdaloidal beds. Some of these are very laumonitic, unpromising, broken stuff, but expose a contact and furnish a good opportunity to determine its dip and strike. Strike N. 65° E., dip to S. E. 20°. Another strike observation is N. 55° E. The contact lies only about 30 feet or so below the crest of the ridge, which is about 150 feet high.

*Minn. Geol. Survey, 21st Ann. Rep't, 1894, Pt. II.

The vein above mentioned is probably parallel to a set of prominent joints; strike N. 40° E., dip to N. W. 70°.

The western part of the Minong territory has not been developed, though I have heard that offers were made for it on tribute. The sketch map, Fig. 1, has no pretensions to accuracy, as I have not been able to get any trace of a mine map, but will serve to illustrate the general relations.

But little later than the Minong Mine, and earlier in organization and in running its course, was the Island Mine. The Island Copper Mining Company was formed in 1873 to exploit a copper-bearing conglomerate, which had been dicovered under S. W. Hill the year before, near the head of Siskowit bay, close to the north quarter-post of Sec. 29, T. 64, R. 37. Prominent in its organization were Messrs. Hardy, Devereaux, F. White, Mason and S. W. Hill. Murdoch was mining engineer, Hardy was agent. Two shafts were sunk, respectively 200 feet and 150 feet deep and 350 feet apart, which were connected on two levels, and a third shaft 350 feet farther west is down 50 feet.* In 1875 a stamp mill was built, but burned down almost immediately. The discouraged company leased the mine to the Equal Eights Tribute Company, of which S. E. Cleaves was a prominent stockholder. The name was later changed to the Island Tribute Company, and E. Vivian, now engineer at Calumet, was in charge. The last season of work was in 1877. When Winchell was there in 1879, things were still in good condition, including the courthouse, for this was once the county seat of Isle Royale county. Now the location is pretty well devastated.

*Swineford, p. 12.

The shafts of the Island Mine are in a conglomerate from 14 to 16 feet thick. The two feet near the foot wall, I am informed, were the rich part. At any rate, while very rich blocks of rock may be found, not the whole thickness of the conglomerate shows copper, by any means. Specimens 14746-14749 illustrate the bed and its foot and hanging. The outcrop is about 230 steps south of the north quarter-post, the east shaft dipping 19°, while the west one dipped 25°. Immediately to the south there is a rise of land with exposures of mottled melaphyres, while to the north the grade is steadily up hill over amygdaloids and beds with agates, of a more acid "ashbed" type. Various facts lead me to identify this conglomerate with bed No. 35 of Marvine's Eagle River section.* It appears to be the first normal conglomerate, with a considerable variety in pebbles, and a generally quartzose or sandy character, that one notices in coming up above the greenstone in each section.

The only other mine that we have to mention that was active during this period, is the Saginaw Mine, on Sec. 35, T. 66, R. 34, near where the Ohio and Isle Royale had worked so many years before. Tim. Nester, of Marquette, was the agent. They began work in 1875, and closed in 1878 or 1879. Their ore was the same as that of the Ohio and Isle Royale, copper finely disseminated in epidote, and hard to stamp. The production of the last three mines above mentioned was:

	Minong.		Island.		Saginaw.	
	Tons.	Pounds.	Tons.	Pounds.	Tons.	Pounds.
1875	24	344				
1876	57	537	24	340		
1877	52	892	44	867	0	1,800
1878	45	596				
1879	36	515			24	1,464
1880	13	1.407				
1881	7	1,397				
1882	10	1,380				
1883	1	1,582				

Table 1. Product of Minong, Island and Saginaw mines, Isle Royale.

*Geol. Surv. of Mich., Vol. I, Pt. II, p. 124. For a full discussion see below, Chapter III, §3.

§ 4. Recent explorations, 1889-1896.

With the closing of the Minong Mine in 1883, the island sank into rest once more. The period of activity was somewhat longer than the preceding period of activity, and the period of repose following very much shorter than the preceding period of repose.

In 1889 the Isle Royale Land Corporation, having much of the estate of the North American Mineral Land Corporation, and adding some smaller areas to it, began work once more. Their estate amounted to some 84,000 acres, and the stock was largely held in England, where, also, the office was, although Jacob Houghton, of Detroit, was one of the largest individual stockholders, and the Consulting Engineer as well; Mr. J. H. Thompson was First President, *i. e.*, Chairman; after him G. H. Feldtmann was Chairman; Leslie was Secretary, succeeded by Alex. H. Hay; W. W. Stockly was Engineer, to whom much of the value of this report is due; and S. S. Robinson, Manager.

Work was begun in June, 1889 (Report Com. Min. Stat. for 1889, p. 26). It consisted merely in trenching and costeaning until August, 1890. Work was first begun in the neighborhood of Todd harbor, around what was known as Haytown, on Sec. 11, T. 65, R. 36, and also on the north flank of the Greenstone range, on Sec. 13 and Sec. 12, T. 65, R. 36, and on Sec. 7, T. 65, R. 35 (Pl. XI). Work was also begun about Washington harbor, which was made headquarters of the company, "Ghyllbank," S. 29, T. 64, R. 38. In August, 1890, an auxiliary company, the Wendigo Copper Company, was formed, to which some of the lands around the head of Washington harbor were assigned (Pl. II). This company began a systematic series of diamond drill holes, which gave a practically continuous section across T. 64, R. 38 (I-K, Pl. XIII). Their other tunnels and explorations were not fortunate, and in 1892 almost all work was suspended, though a small party was left to finish drilling two holes on the extreme northwest of the section, close to the water's edge. It was the extreme and unique value of the geological column afforded by these drill cores, which promised to be the key, not merely to the geology of the island, but perhaps to the stratigraphy of the Keweenaw series in general, and even to throw light also on broader questions of the successions of eruptive rocks,—questions of world-wide significance,—which caused the State Geologist to feel that this material must be saved to science at any cost, even though it delayed publication in other directions. Moreover, this cross-section was the last thing finished of the explorations, so that none of the ground shown up by it has been farther tested. It was thus of the highest importance for the future explorations that the record and results of these explorations should be saved. Therefore I spent the time between August 4 and November 10, of 1893, with Chas. LeSage, boatman, and W. W. Stockly, the Engineer of the Wendigo Copper Company, in going over the drill cores, some 9,000 feet, taking notes and samples, and in visiting and taking notes of the explorations in other parts of the island. At that time the secretary of the company, Mr. Hay, was there, and the Isle Royale Land Corporation has kept and is still keeping some one in charge of the property, so that the diamond drills are still there in good order, ready to renew work. The company has also had other plans for the development of the island as a summer resort, and for the exploration of its timber. There are a large number of fishermen that set their nets around the island every summer, and the steamer Hiram E. Dixon stops at the island during the summer season, on her way from Port Arthur to Duluth. The island is also frequently resorted to by camping parties from Duluth, and John F. Johns lets a cottage on an island north of Washington Island to such parties, or they camp in tents or in the deserted lighthouse at Rock harbor and at other points. The picturesque beauty of the island is only faintly indicated by some of the illustrations of this report (Plates VIII, IX, X, XIV, taken from negatives made by Mr. Stockly), and every one who has been there has sung its praises. The scenery is of that fiord type of scenery, which lends such a charm to the coasts of Maine and Norway, and is not unworthy of comparison with them. It is not surprising, therefore, that the company aforesaid planned to make a summer resort on the island. Rock harbor was the place they had fixed on, and a town site has been surveyed, on Sec. 28, T. 66, R. 34, close to the location of the erstwhile Ransom.

Between September 16 and October 12, 1895, I revisited the island with R. T. Mason, assistant, D. C. Forbes and G. Wallace, partly to get farther barometric data, and partly to examine more carefully the region between Rock harbor and Siskowit bay. I n the meantime no work had been done there by miners.

The history of these latest explorations (I trust it is not yet finished), must be gathered from the local papers and from private data. Further accounts of these explorations are given in various places in this report, for I have not attempted to summarize them in this historical chapter. The special Regatta Edition of the Duluth Evening Herald in July, 1890, contained under the heads "Lotus Land of the Lake," p. 7, and "A Western Mecca," p. 10, some accounts of the plans of the Isle Royale Land Corporation and its auxiliary companies. In the summer of 1896, Mr. Jacob Houghton continued explorations on the vein running near drill-hole No. 4 or No. 5, but these explorations were suddenly brought to an end by the failure of a Duluth bank.

A word, in closing, on those maps of the island which appear to have incorporated original observations.

The first map of which I know, is that of the Jesuit missionaries in 1670-1671, reprinted by Foster and Whitney.

In 1825 there was a chart of the Canadian shore prepared for the British Admiralty by Capt. Bayfield, which included a delineation of Isle Royale and soundings around it, which were used on Foster and Whitney's map.

Then in Executive Document No. 5, accompanying the Annual Message to the 31st Congress, 1849, there are two maps:

The first, by C. T. Jackson, United States Geologist, shows the locations of the veins, and of the various explorations, and gives the swamps in detail, but is not as accurate in its delineation of the sandstone conglomerate at the southwest point of the island, as the other.

The second was prepared by J. W. Foster and J. D. Whitney, with the assitance of S. W. Hill and S. W. Chlatter (*Sic!* Schlatter). One or two locations are given on this map that are not given on Jackson's, and the sedimentaries are more fully indicated. It is the best geological map of Isle Royale heretofore published.

In their final report, Pt. II, in 1851, Pt. I having been printed the previous year (Senate Special Session, March, 1851, Executive Document, No. 4) was included a general geological map of the Lake Superior Land District, with a small map of Isle Royale. This adds nothing to the large map before mentioned, and is less accurate than that in bringing the conglomerate at the southwest end of the island still farther to the south.

In 1864 was published what is known as the Hulbert map, com- piled and drawn by J. C. Booth and E. J. Hulbert, with geological notes from Foster and Whitney, S. W. Hill, W. H. Stevens, N. (*sic!* H. F. Quarre?) d'Aligny and Ed. J. Hulbert. The conglomerate band from Siskowit bay to Rainbow cove is too far south, as on Foster and Whitney's small map, and probably unintentionally the region south of it is colored trap instead of sandstone.

In 1871 S. W. Hill published a map very different from any that had preceded it. The south boundary of the trap range is brought north again to where it was given by Jackson, and a belt sketched nearly parallel to it, running from Scovill point to Huginnin cove, which does not correspond to any geological feature that I have observed. There are a large number of veins noted. If we knew on just what data these were drawn in, and how far they represented the results of Hill's extensive explorations, they might have much more value. But as the map was issued in 1871, the year his explorations began, it has probably more the character of a prospectus.

In 1871 the U. S. lake survey chart of Isle Royale, with detail charts of the more important harbors, was published. The scale of the principal map is 1:120,000. This is beautifully engraved and covers all but a small part of the interior of the island. Much of the island was contoured, and these contours have been the base of the contour map of the island now being issued by the United States Geological Survey.

In 1892, Mr. Stockley compiled a map, using U. S. Linear Survey notes for section lines, township plats of the Land Office for shore lines, and original surveys; this map has had a considerable circulation in blueprint form, and was the base used in our geological researches.

Mr. Stockly, however, discovered that these plats had not been made from a careful platting of the original Government field notes, and consequently he undertook the task of computing the whole matter over again, a herculean task, when one considers the amount of meandering there is in the island. The resultant map is the base used for this report, and we may fairly boast of having the most accurate map hitherto published. The original Land Office notes by Ives have been supplemented so far as needful, from our geological note books, Mr. Stockly's surveys, and the Lake Survey chart. But it should be said that Mr. Ives and his assistants did work of a much higher character than has often been done since his time for the Linear Survey. The errors of closings are small, the work having been done with the solar compass, and magnetic variations, rock-ridges, etc., are carefully and frequently noted. In this brief resume, only those maps have been noted which are supposed to have incorporated original material, and this rules out such maps as that of Irving, in "Copper-bearing Bocks of Lake Superior" (Pl. XXVII), because none of his parties visited the island.

CHAPTER II. CONSTRUCTION OF CROSS SECTION FROM DRILL RECORDS

§ 1. Deviation of drill holes.

Before we proceed to give an account of the succession of rocks revealed by the Wendigo Company's borings, I have thought it well to give some account of the method of construction of a cross-section. The use of the diamond drill is comparatively new, and but little can yet be found in the literature upon the method of treating such records as the drill may give, and of avoiding the errors to which one is liable in constructing a section from them. This chapter may therefore serve a double purpose,—as a credential for our work, and as a guide to others who have similar work.

In our work we have had to assume that the drill holes were straight, and with one exception vertical, as they were intended to be. This is a good deal of an assumption, for a diamond drill is in this respect very different from a churn drill, where any considerable deviation from the vertical is sure to make trouble. In the diamond drill the drill is being pressed and not dropped into the earth, and however stiff a few feet of the rods by which it is pressed may seem, the discussion at the second annual meeting of the Lake Superior Mining Institute, March, 1894,* showed plainly that they would easily bend as much as 6 feet in 50 feet and the experiments of Mr. Channing, there recorded, show that his inclined holes went very much astray. By using a tube with 20% of hydrofluoric acid to etch the glass, he measured the dip of his holes at various depths.

*Vol. II, pp 23-32.

"The final method of work was as follows: A blank tube was put in the combined bit and core shell from the top end until the lower end rested on the spring. Holding this in position it was laid beside the core barrel so that the length of thread was allowed for, and a file mark made on the barrel core just even with the top of the glass stopper. A dry wooden plug was made to fit the core . barrel and driven In until it just cleared a point corresponding to the file mark. The core barrel was now clamped in a vise in a nearly vertical position.

"The stopper of the tube was held in a tin spoon with a little paraffine over a candle flame and the upper end of the tube warmed. An inch of 20% hydrofluoric acid was carefully poured in the tube, then an inch of water and the stopper taken from the melted spoon of wax, smartly rapped to throw off any excess of paraffine and quickly put in the tube. The acid immediately heated up the tube but no ill effects were felt from this. Wrapping a thread or two of lamp wicking around the neck of the tube, it was put in the core shell and still holding it in an upright position the upper end was introduced into the core barrel and the thread between the shell and the barrel screwed up. Carrying the barrel in an upright position it was put down the hole and no special pains taken in lowering the rods, save to touch the bottom of the hole carefully." His results were roughly as follows:

Hole No.	1	2	3	4	5	6	7	8	9
Deviation in degrees per hundred feet	4°	5°	3°	12°	12°	8°	8°	8°	4°

The cause of this deviation he attributes to the weight of the core barrel in a slightly larger hole inclining the drill upward.

So far as this cause is concerned, we see that it will not operate so much in a vertical hole. Moreover, in a vertical hole there is no reason to suppose that the deviation will be constantly in one direction, and if the deviation is at random, the drill hole will describe an irregular spiral, and such cases have been, known. For instance, Mr. W. W. Stockly reports a case where a shaft 8 feet square, in following a vertical drill hole, found it describing a spiral, and at 500 feet depth it had shifted from the center to the corner of the shaft, and then disappeared for good. We shall need to correct our measurements by multiplying them by the cosine of the angle which the hole makes with the vertical. As long as the deviation from the vertical does not exceed 8°, the consequent correction will not be more than 1 per cent. It is not probable, therefore, that in assuming our drill holes vertical we make any considerable error. This is also shown by the way our results check up.

§ 2. Determination of dip and of true thickness of bed.

A certain amount of the softer rock is ground away, but in general the drill cores show us pretty well the vertical width of the several beds along the drill holes. Now, beside this, we must also know the dip, to get the true thickness of the bed. We have the following methods of obtaining the dip:

(1) By the lines of bedding or of flow, which we often observe running across the drill core. Thus, holding the drills vertical, we can measure the dip directly from these lines. Of course, we cannot discriminate small irregularities or cross-bedding in this way.

(2) By field observations of the dip on adjacent outcrops. Unfortunately we have seen no outcrops of sediments close to the drill holes. Observations of contacts of flows are important, but observations based merely on the attitude of the joints of a rock can not be trusted for precise results, though the columnar jointing more or less at right angles to the surface of cooling, and a parting about parallel to the same surface, often give a clear idea of the general dip.

(3) By comparison of the depths at which some bed, so characteristic as to be surely identified, is found in different holes. The strike of the rocks and the relative altitudes of the drill holes being known, this is much the more accurate way of determining the dip, and also enables us with great certainty to piece on to the record of one hole that of another. It requires the drill holes to be near enough or deep enough to overlap. This, unfortunately, is only twice the case in the Isle Royale drill cores, to such an extent that we can identify corresponding beds with absolute certainty. It is a penny-wise pound-foolish policy to let the drill holes only barely overlap, for the sake of saving the cost of a few extra feet, when thereby the uncertainty of the whole section is greatly increased, when, too, the proving of the same bed at diferent points is of interest.

It is obvious that this method of overlap gives us what may be called the average dip between the drill holes, which might be slightly different from the dip at any one drill hole, and if the strike were so different at the two drill holes that it was not permissible to use an average strike, the problem would be much more complex, and new factors would be introduced. Assuming dip and strike as constant between two holes, we have the following simple reckoning. In Fig. 2 let A be the position of the bed in drill hole No. 1 and D the position of the same bed in drill hole No. 2. Let DE be a horizontal line parallel to the strike of the bed. All points of DE will then lie in the bed and be at the same time in a horizontal plane. Let AC be a line perpendicular to DE at C through A. It will also lie in the bed and be the direction of dip, since it is perpendicular to the strike. Let B be directly below A on the same level as C and D. Then the tan of the dip, which is ∠ABC, = AB : BC. But AB is equal to the difference in level of A and D. Moreover BC=BD. sin ∠CDB. This angle ∠CDB is the difference of the direction of the strike and of the direction of drill hole No. 1 from drill hole No. 2.

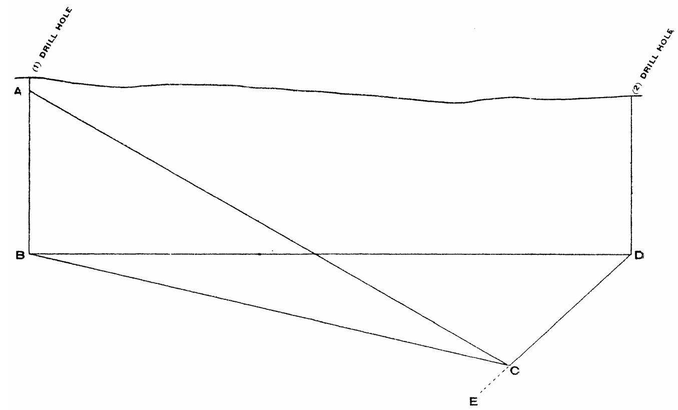


Fig. 2

Figure 2. Illustrates the computation of the dip from observations upon the same bed, at A in drill hole (1) and at D in drill hole (2).

Thus if a^1 be the altitude of the top of drill hole No. 1, and
a^2 be the altitude of the top of drill hole No. 2, and
d^1 be the depth of the bed in drill hole No. 1, and
d^2 be the depth of the bed in drill hole No. 2, and if

s be the strike, and b the bearing of hole No. 1 from hole No. 2, and the distance between the two holes, *i. e.*, BD, be 1, then tan

$$\text{dip} = \frac{AB}{BC} = \frac{(a^1 - d^1) - (a^2 - d^2)}{l.\ \sin\ (s-b)} = \frac{(a^1 - a^2) - (d^1 - d^2)}{l.\ \sin\ (s-b)} = \frac{(d^2 - d^1) + (a^1 - a^2)}{l.\ \sin\ (s-b)}$$

If the bearing of drill hole No. 1 is nearly at right angles to the strike, so that (s--b) is near 90°, but the dip is not great, an error in estimating the strike will not produce nearly as great an error in the dip. Such is practically .the case before us. Moreover, if we take the distance apart of the drill holes, from their projection on a cross-section perpendicular to the strike we at once obtain the denominator l. sin (s--b). There is another more serious error liable to be encountered, in that a fault may have intervened so that the bed ACD will not be continuous. This is certainly a serious feature of this method of determining the dip. It can be guarded against only by watching to see if either set of drill cores show signs of such a fault, by examination of the surroundings to see if such a fault be geologically likely, and by checking up the results by other methods. A modification of the third method consists in connecting the outcrop of a bed with its position in the drill hole. In such case the outcrop may be considered as though it were at 0 feet depth in another drill hole.

(4) The fourth method of finding the correction for dip is hardly a method by itself, but consists in certain general considerations of analogy and structure, which may serve as a check upon the previous methods. Thus we may argue from the analogy of the Keweenawan series elsewhere that the dip should flatten in going toward the top of the series.

§ 3. Combination of records of different holes.

Having corrected the beds in each drill hole from their vertical width along the drill hole to their true thickness, the next step is to combine the records.

(1) If the drill holes overlap, so that each cuts the same bed or beds, and these are so distinct that we can recognize the same bed in the two holes, then when in constructing our geological column we come to this bed, we can pass from the one hole to the other and continue the record.

(2) If we cannot be sure which are corresponding beds, or if the holes do not overlap, then we can find to what point in that drill hole which is the higher in the series, or in the hypothetical downward continuation of that hole the top of the other drill hole does correspond,—provided we have found the dip in some other way,—by using the formula on page 31 and merely working the problem (8) backward. For in this case placing $d^1 = 0$, we may rewrite the formula given on page 30 in a form from which to find d^2; thus $\tan(\text{dip})\ l. \sin(s — b) — (a^1 — a^2) = d^2$. This method should also be used as a check on others. But here, as before, faults may cause us serious error.

§ 4. Effects of faults.

Faults going across the strike are in general steep on Isle Royale, and we shall be warned of their probable existence, if they cut the drill hole, by considerable streaks of vein rock. Faults running with the strike would be much more readily confused with the contact of the two flows, especially if they follow the same as they often do. Let us then consider what the effect on our record would be, of the various classes of faults.

In the first place we can see that a simple slide like the Allouez slide (at Eagle River gap, Keweenaw Point) exactly accordant with the dip and strike, will not disturb the record at all. Faults with a dip flatter than the dip of the beds, and the upper side sliding down, are not likely to occur. Now, for simplicity's sake, suppose our series of beds to dip southerly, as, in fact, they do, and let us first consider faults that practically coincide with the strike of the formation. We lose no generality in assuming that the beds dip south, if we give the faults all possible directions, and the assumption will shorten our expressions. Now, in strike-faults we shall consider first:

A. The south side thrown down. Fig. 3.

If we estimate the dip from a bed in hole No. 2 below the fault, and in hole No. 1 above it, we shall err in making the dip too steep. If we have obtained the dip in some other way, then suppose,—

(1) Hade of fault either way, north or south; fault between two holes, cutting neither. In this case, Fig. 3, we may under-estimate or ignore the gap between them, or, if they ought, according to the distance and gap between them, to overlap, we shall find at depths at which certain beds should correspond, beds which did not correspond, and if we could force them into correspondence, assuming for example that bed A of hole No. 1 was equivalent to bed D of hole No. 2, instead of bed C, we should make our geological column shorter than it ought to be.

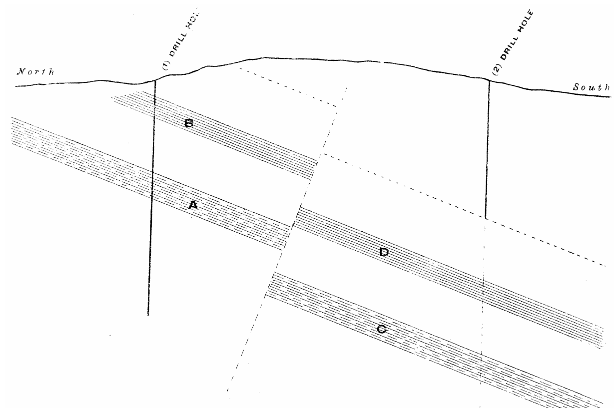


Fig. 3

Figure 3. Illustrates the effect of a fault hading north, which throws the south side down and cuts neither drill hole.

(2) Hade of fault to north, and the south hole (No. 2) passing through from above the fault to below it, Fig. 4. There will be a repetition of beds in the neighborhood of the fault. We shall be in danger of supposing in case, for example, hole No. 2 stops at bed D, that they fill a part of the column occupied by a gap really unknown. If the holes are so near that without a fault they would overlap, we shall find that the lower part of hole No. 2 does not correspond to No. 1, as we should expect, and thus probably be warned of the fault. Finally, by correlating C with F we might possibly be led to imagine too steep a dip.

(3) Hade of fault to north, as before, but the north hole (No. 1) is cut by the fault. The effect, so far as correlation is concerned, will in general practically be the same as when the north hole does not go down far enough to reach the fault, case (1), since we should naturally use the top of the north hole (No. 1) to correlate with the bottom of the south hole (No. 2). Below the line of the fault, correlations could be made directly with the south hole, and in the record of the north hole there would be a reduplication of beds.

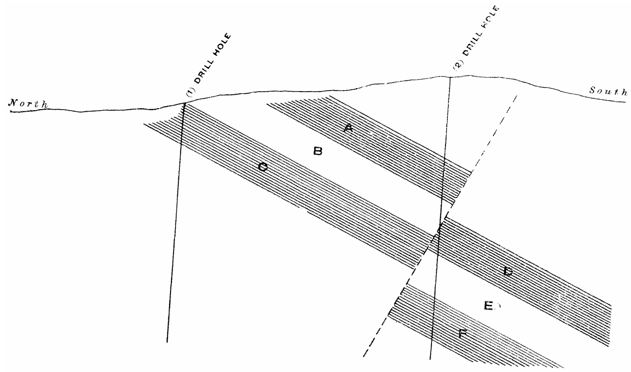


Fig. 4

Figure 4. Illustrates the effect of a fault hading north, which throws the south side down and cuts the south drill hole.

(4) Hade to south, and north hole cut by fault. There will be no extra difficulty in correlating the beds. The record of the north hole (No. 1) will be deficient by some beds, as is obvious from Fig. 5, unless indeed the fault is one with a very flat dip; flatter than that of the beds, in which case it would be likely to cut both holes.

But such flat faults are not known except as over-thrusts as previously noted. Such a fault would cause reduplication of beds in the record of (1).

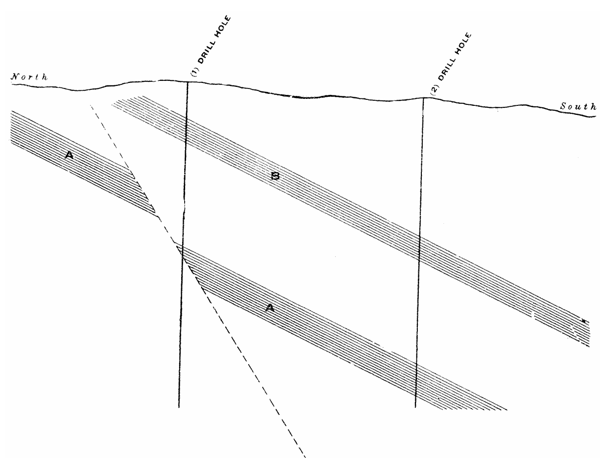


Fig. 5

Figure 5. Illustrates the effect of a fault hading south, which throws the south side down and cuts the north drill hole.

(5) Hade to south, and south hole cut by fault; dip of beds flatter than dip of fault. Fig. 6.

If the north hole is near enough to, overlap the bottom of the south hole, true correspondences and dips can be obtained by matching the beds, from the bottom of the south hole up to the fault, *i. e.*, to D, in Fig. 6.

Then there will be a loss of certain beds. If the north hole also contains a bed which can be recognized in the upper part of the south hole, e. g., the bed B, the missing beds will be found in the record of the former; the dip computed from the two occurrences of the bed B will be too steep and the fault will be detected. Compare the correlation of drill holes IX and VIII, in chapter III. In this case (5) there is danger of establishing a false correspondence, for suppose that B and A, Fig. 6, of the south hole are assumed to correspond with B and A of the north bole, when really they are equivalent to B' and A', which were not cut by the north hole, while the real A and B have been cut out by the fault. In this case, or if we could not match any beds above the fault, and yet were not aware of the discordance, because the north hole was so far away that its highest bed would come below the fault in the south hole, we might leave beds out of our series unawares.

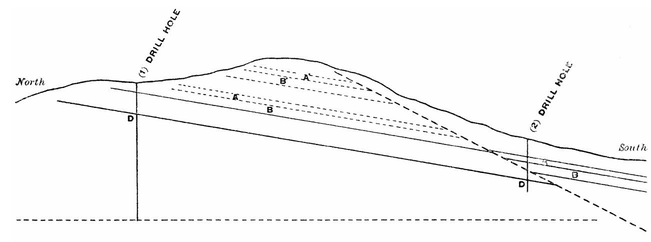


Fig. 6

Figure 6. Illustrates the effect of a fault hading south, which throws the south side down and cuts the south drill hole.

If, then, the holes are so deep and so near together that normally the beds cut by them should overlap somewhat, one case may occur where there is great liability to error,—that is when, with no duplication nor correspondence of beds to warn us, the hade of the fault is to the south and the south hole is cut by the fault so high up as to be out of the way of the matches with the north hole.

B. The south side thrown up; dip of fault if to south, steeper than dip of beds.

(1) If neither hole is cut by the fault, Fig. 7, if we estimate the dip of beds from the boles, we shall make it too flat, or possibly even find it the wrong way. If we get our dip in some other way, we shall be in danger of getting our column too thick by repetition of beds. If then we find the bottom bed B of the south hole (No. 2) match the top bed A of the north hole (No. 1), we shall see if the dip thus derived (by method (3) on p. 63), agrees with what we should otherwise expect. If it is abnormally flat, we may suspect a fault of this class.

(2) If the north hole is cut by the fault with a south hade, we are not so likely to err in dip or correlation, but there will be a reduplication of the record in that hole, which may again lead us to to get our column too thick.

(3) If the south bole is cut by the fault with a south hade, we shall have a reduplication of record as before, and while the correlations, below the fault, of the top of the north with the bottom of the south hole will be all right, those above will give dips too flat.

(4) If the north hole is cut by the fault with a north hade, we have the case shown in Fig. 8, between holes No. 2 and No. 3. This is an especially important case to discuss, as Lawson has suggested that it occurs frequently on the north shore of Lake Superior adjacent to Isle Royale.* In a case of this kind we shall be unable to correlate the top of the north hole, No. 2, with the

bottom of the south hole, No. 3, correctly, and shall be likely to make our geological column too thick, by reduplication of beds. The means of detecting this kind of fault will be by the recurrence of the same beds. For example, the set of beds A will occur again at a higher level south of the fault. Of course, if the throw is very great, they may occur at a considerable distance south beyond the hole next south of the fault, and be found only in some higher hole. We shall have to look over our records to see if there is any such recurrence in the succession of beds as to warrant the idea of such faults.

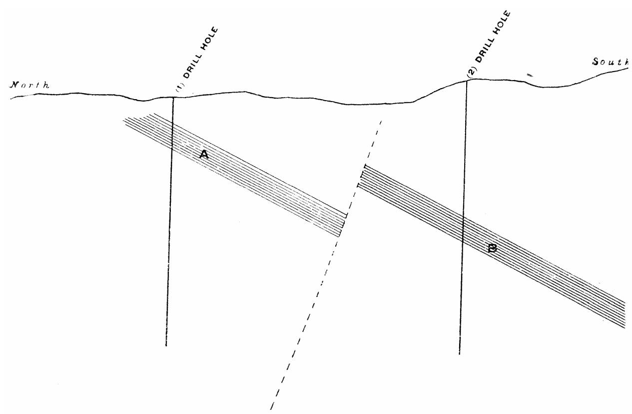


Figure 7. Illustrates the effect of a fault hading north, which throws the south side up and cuts neither drill hole.

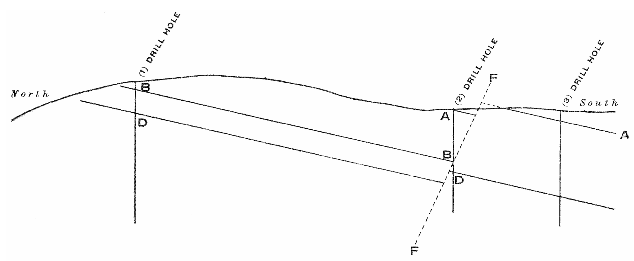


Figure 8. Illustrates the effect of a fault hading north, which throws the south side up and cuts either drill hole.

*20th Annual Report, State Geologist, Minn. p, 192; also Bulletin No. 8, of same survey, pp. 33, 39, 45.

(5) If it is the south hole which is cut by the fault with a north hade, Fig. 8, holes No. 1 and No. 2, the difficulties and dangers will be much as in the preceding case. If the holes are so near together that there is an overlap above the fault, then the correlation can be there correctly made, while beds below the fault will give dips too flat.

In any and all of the above cases, if the fault cuts both holes, the relations of the parts of the holes that are on the same side of the fault will be normal, and of the parts on opposite sides of the fault abnormal, following the appropriate cases above. In such cases, inasmuch as the hade of the fault is steeper than the dip, the holes must be quite near each other, and with south-hading faults there will almost certainly be at least two corresponding beds, and there should be no difficulty in noticing the fault, unless the beds are extremely uniform and similar. In the north-hading faults, at the bottom of the north hole, we ought to find a bed that will correspond to one in appropriate position in the south hole, while the lack of correspondence in the upper part of the hole would tell the story of the faulting.

There remains to consider:

C. Hade of fault flatter than dip of beds. In this case, as we have it is almost invariable that the throw is up, as it is hard to conceive the mechanics that would lead to a down throw on a, plane flatter than the dip. But reverse faults, so-called thrust planes, are mere to be expected.

(1) Neither hole cut. This would not happen if the holes were planned to overlap at the normal dip, when undisturbed, and. hence is an unimportant case. There will be no possibility of correlating correctly.

(a) If the south side is thrown up,—thrust,—the gap in the column will be greater than supposed. The geological column will be made too short.

(b) If the south side has slid down, the gap in the record will be less than supposed. The column will be made too long.

(2) If the south hole alone is cut, below the fault line it may correspond to the north hole. At the fault line,—

(a) If the south side is thrown up,—thrust,—there will be a gap in the geological column unsuspected, at the fault, and the geological column will be made too short.

(b) If the south side has slid down there will be a repetition in the series, and the geological column will be made too long.

(3) North hole cut. In this case the south hole also must be cut, if they are near enough to correspond. Below the fault the two holes may correspond and be correlated, and a correct dip be derived.

There may also be a correlation above the fault line. The series between will not correspond.

(a) If the south side is thrown up, there will be a gap of unknown size in the column, possibly two. We may or may not be able to piece out the record from the four parts of the column given.

(b) If the south side has slid down, there will be a reduplication in the series and we ought to be able to detect the fault and correct the series, if the beds are sufficiently characteristic. It will be noticed that, in a series of drill holes planned to overlap, all faults will tend to produce repetitions of the beds, if the hade is to the north or the direction of downthrow is to the north, except in the case of flat overthrust faults. If corresponding beds can be noted, the abnormal dips that would be derived from them generally give a clue to faults. The only faults that cannot be thus detected, if the holes are properly spaced and there is enough variety in the beds to admit of correlations, are—a normal fault with dip south, greater than that of the beds;—a reverse fault with dip south, less than that of the beds.

In regard to faults that do not coincide in strike with the beds, we need consider only that component of the motion which is up or down, and the angle at which, the faults cut the plane of dip, and having found their projection on the cross-section, we shall find that the same rules apply as above, since the drill holes give us information only concerning the vertical position, and will be not at all concerned with the displacement in other directions. We may also look at it in another way. In our cross-section the boundary between that part of the beds which we consider undisturbed by the fault, and that part which we consider moved by it, will be given by the projection of the plane of the fault on the plane of the dip, and the motion of the disturbed part, which is of course parallel to the plane of the fault, may be resolved into two parts, the one along the line of projection and the other horizontal in the direction of the strike, which we need not consider.

In order fully to grasp this case we shall need to use some projection like the stereographic, which I have used for other purposes, and of which a description will be found in Dana's larger mineralogy and also in Bull. Geol. Soc. Am., Vol. II., pp. 365, 368, Pl. 14. We will apply this particularly to the discussion of two classes of faults, which we know occur on Isle Royale, and may be expected to occur in our cross-section. The first class is well exemplified at the entrance to Chippewa Harbor. These faults are parallel to joints running nearly east and west, more so, at all events, than the strike, and they dip at about 70° to the north. The second class occurs at various points, and fault the Minong trap. One probably comes out near Huginnin Cove. Another lies evidently between drill holes No. XV and No. XVI, which are both close to the northwest shore of the island, throwing No. XV, which is northeast of No. XVI, up about fifty feet, and apparently throwing the outcrop to the right or southeast in going northeast. This throw can be seen 25 chains, *i. e.*, 1650 feet, west of the southeast corner of Sec. 19, T. 64, R. 38, and about 500 steps west and 200 steps north of the southeast corner of Sec. 16, T. 64, R. 38.

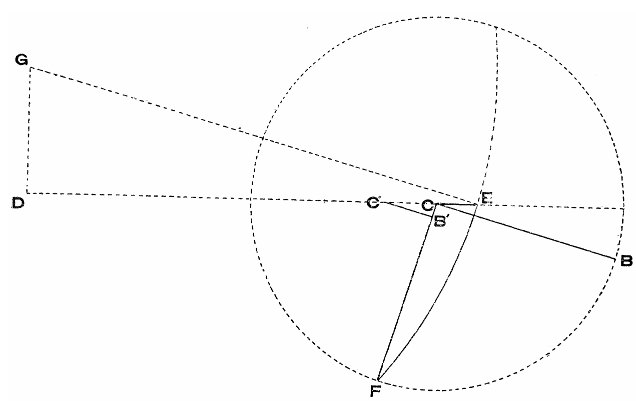


Fig. 9.

Figure 9. Illustrates by a stereographic projection the displacement of the bed C^1B^1CB by a fault, CEF, of the Chippewa Harbor type.

Let us study to what classes these faults respectively belong, and what effects they would produce. Figure 9 illustrates the Chippewa Harbor type in stereographic projection. To understand it we must imagine ourselves at the horizontal level looking northeasterly in the direction of the strike of the formation, so that a line representing that strike would be foreshortened to mere point at C. Then the dotted circle represents an arc passing through the zenith, and the area within it represents half the universe) and any direction at right angles to the strike will be represented by a radius of that circle r; thus CB may represent the dip of the beds. Any direction not perpendicular to the strike will be foreshortened more or less. Thus CE may represent the direction east, which we will also take as the direction of the strike of the faults. According to the principles of the stereographic projection, then, $^{CE}/_{r}$ is equal to the tangent of half the angle between the strike of the beds and the strike of the fault, which is in the present case about 25°. The angle ECB is, of course, equal to the dip of the beds. To get the dip of the fault in the direction of the dip of the beds, we draw EG, making an angle with the horizontal EC equal to the overhang or hade (the complement of the dip) of the fault. This angle is taken on that side of E toward which the fault dips. Then we also take on the opposite side of C from E a distance CD, equal to the cotangent of the difference in strike of fault and beds—in the case of the Chippewa Harbor fault about 25°—and erect a vertical which cuts the line EG at G. Then G thus found will be the centre of a circle EF, which will cut the dotted circle "primitive" at F. Then by the theory of the stereographic projection, CF will be where the fault will cut the plane of dip, which is the plane of projection, and CEF will represent the fault plane.

Going along the strike of the beds to the northeast, at Chippewa Harbor, we And the outcrop thrown to the left as at C'; thus to the north of the fault the bed CB will be displaced to C'B'. We see then that the fault belongs to the class B 4, with downthrow and hade to the north, and is a normal fault. *It will be noticed too that CF is nearly perpendicular to CB, as if the fault had been influenced somewhat by joints perpendicular to the bedding, which are common in all formations, but especially in igneous rocks.*

Turning now to the second class, represented in Fig. 10, we find the strike of the faults near north, generally a trifle east of north. Then the strike of the beds being foreshortened to the point C as before, inasmuch as the strike of the beds is near N. 55° E., the strike of the faults will lie to the left and will be represented by the line CN foreshortened somewhat, and proportional to tangent ½ 55° This class of faults is very nearly vertical, sometimes dipping a little to the east, sometimes a little to the west. Of course if such a fault were exactly vertical, a vertical drill hole once in it would never get out of it. Such a fault occurring between two drill holes would produce the same effect whether it had a slight hade one way or the other. We will assume for our drawing a slight hade to the west which is perhaps the more common. Then, just as before, we lay off CD equal to cot 55°, find G, the intersection of the perpendicular at D with a line making an angle with the horizontal equal to the overhang or hade, and about G describe the circle NF. NFC once more represents the fault plane. Going northeast along the strike, that is, in the direction of C, we find the outcrop thrown to the right. Thus, crossing the fault plane NCF we find C' thrown to C. Thus the east side of the fault is thrown up and the west side down. Thus we see that these field observations on the outcrops harmonize perfectly with what the records of holes Nos. XV and XVI show us. This class of faults, though so different in strike, would then be of the same group as the Chippewa Harbor, northward-hading normal faults, the fault-plane being nearly perpendicular to the plane of dip.

In Chap. Ill, at the beginning of the description of drill hole No. XIII, there is further study of a fault of this class, which probably affects this drill hole and XIIIA.

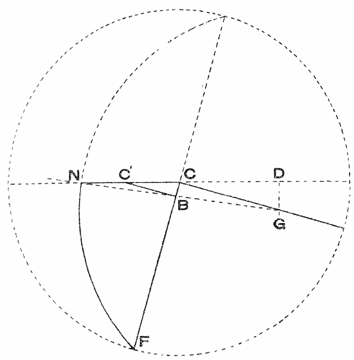


Figure 10. Illustrates by a stereographic projection the displacement of the bed CG-C1B by a fault, NCF, of the Huginnin type.

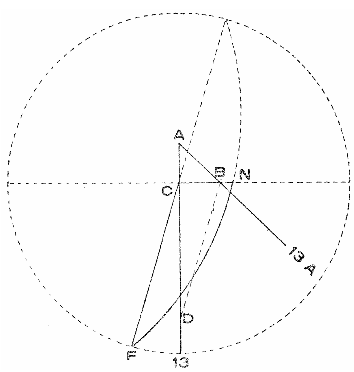


Figure 11. Illustrates by a stereographic projection the displacement of the fault at drill hole No. XIII.

§ 5. Description of records and drill holes.

At the bottom of our record we have three drill holes all close to the northwest shore of Isle Royale and not much above Lake Superior. Holes Nos. XII and XV are on Sec. 16, T. 64, R. 38, and No. XVI is just over the line to the west on Sec. 17 adjacent. Of No. XII Mr. Stockly kept track down to 1038 feet which, as we know, was within sixteen feet of the bottom, and although the drill house with boxes, etc., was burned, I was able to get a few scattered samples, especially some which are without doubt from the very bottom of the hole, at 1054 feet, and thus to see that the bed of porphyry had not changed from what it was at the bottom of hole No. XVI. The remainder of these three holes were drilled after, Mr. Stockly left the island, and the records may not have been so carefully kept, but they agree so well with each other and with Mr. Stockly's record, that I think we may depend upon them in a general way very well.

A word should be said as to how the samples were kept. Boxes were made the width of a board and about five feet long, divided by strips of wood into partitions the width of a drill core. There were generally five rows, so that if all the core was saved there would be just 25 feet of it in a box. But the amygdaloids and softer beds ground away somewhat into sludge, so that sometimes there would be more than twenty-five feet of strata represented in the box. The depth in feet for every raising was placed alongside the sample, on the partition, in pencil; the number of the hole, and the top and bottom depth represented were marked on each box. Thus, while there is some liability to error in the location of a sample, it is likely to be confined to five feet, and if not to that, at least to the range of the box. The samples in the top of hole No. XIII, from 31 feet to 113 feet, got mixed. The holes are located by survey on the map of the Wendigo property (Pl. III) and the altitudes were obtained by Y level. In the table below, their locations and elevations are given, and the distances between them projected on a line running N. 30° W., which Stockly took as the direction at right angles to the strike, after careful observations at the holes, as well as at a number of test-pits between the holes. These distances are scaled from a blue print, the original map not being extant, and are liable to an error of 1:120. He found the dip in general to be about 15°, and in particular, from observations on the Minong trap in No. 5 tunnel and in No. 1 drill hole, he determined the dip as 14° 15'. These figures agree fairly with my observations, as recorded on the map of Isle Royale and in the geological column, except that I thought I observed that the dip increased slightly on the N. W., and especially on contact planes near the shore I got some good observations of 18°. On the whole, we cannot pretend for our work a greater accuracy than within 1 per cent. The dips derived from the correlations are given in connection with the geological column.

CHAPTER III. THE SUCCESSION OF ROCKS.

§ 1. Introduction.

It is my object in this chapter to give an account of the succession of rock beds on Isle Royale revealed by the borings of the Wendigo Company, and by outcrops, and in this connection I shall try to give such an account of the rocks as may be understood by any intelligent mining man or explorer. Many of them are exceedingly fine grained, and their true mineral composition can be found only by examining thin sections under the microscope.

The detailed account of microscopic work, however, and other technicalities, will be left to later chapters, or, where such may best be introduced in this chapter, it will be in. finer print. I shall at the .same time give my correlations with the beds on Keweenaw Point, and my reasons for the same, in so far as they are not too technical.

Table of Drill Holes of Wendigo Copper Company.

1. No.	2. Lat.	3. Dep.	4. Sec.	5. T.	6. R.	7. Alt.	8.	9. Distance apart. Chains	10. Distance apart. Feet.
I.	S. 9 55	E. 22.21	¼ S., 20:21	64	38	163.7	XII	....	....
II.	S. 19.95	W. 15.51	Cor., 21:22; Cor., 28:27	64	38	407.0	XIV.	19.70	1300
III.	N. 4.18	W. 0.37	¼ S., 20:21	64	38	231.0	XIII.	23.00	1518
IV.	S. 0.64	W. 6.02	Cor., 21:22; Cor., 28:27	64	38	194.0	III.	26.90	1775
V.	N. 21.09	W. 7.83	Cor., 21:22; Cor., 28:27	64	38	56.0	I.	23.00	1518
VI.	S. 45.28	E. 45 23	Cor., 21:22; Cor., 28:27	64	38	341.0	V.	31.70	2092
VII.	S. 65.70	E. 65.80	Cor., 21:22; Cor., 28:27	64	38	262.6	IV	19.60	1293
VIII.	S. 0.96	E. 8.65	Cor., 27:26; Cor., 31:35	64	38	376.3	II.	27.40	1808
IX.	S. 28.16	E. 29.22	Cor., 27:26; Cor., 34:35	64	38	232.5*	VI.	36.40	2402
X	S. 50.19	E. 51.13	Cor., 27:26; Cor., 34:35	64	38	206.7	VII.	28.00	1848
XI.	S. 0.39	W. 11.54	Cor., 35:36; Cor., 2:1	64; 63	38	143.0	VIII	24.00	1584
XII.	N. 9.36	E. 6.31	¼ S., 16:17	64	38	10. ±	IX	33.60	2218
XIII.	S. 2.63	E. 2.24	Cor., 17:16; Cor., 20:21	64	38	216. ±	X.	29.90	1973
XIV.	N. 24.00	E. 1.77	Cor., 17:16; Cor., 20:21	64; 64	38	198. ±	XI.	33.20	2191
XV.	N. 13. ±	E. 13. ±	¼ S., 16:17	64	38				
XVI.	N. 3. ±	W. 2. ±	¼ S., 17:16			20 or less	-----	---------	------

Table 2. Drill holes of Wendigo Copper Company.

*Measurements began at rock, *i. e.,* with an altitude 202.5 ft.

The A holes (12A, 4A, 7A) were bored from the same setup at an angle of 45° to the NE. No record of 4A nor of 7A was kept.

In column 1 are the holes in numerical order; in column 2 the distance of the drill hole north; in column 3 its distance east or west in chains from the quarter section post or section corner given in column 4. For XV and XVI the locations are only approximately scaled from note book of A. C. Lane. We have in column 5 the township. The range is always 38. In column 7 is the altitude, close estimates merely for holes XII to XVI; in 8 the holes are arranged in order from NW to SE. Their distance apart in the direction of N. 30° W. is given in chains in column 9; in feet in column 10.

A. Mineral ingredients.

The rocks of the island are a set of old lava flows, and of sediments apparently derived almost wholly from the lavas or from similar rocks. The mineral ingredients of these lavas are often too fine grained to be recognized with the naked eye, and consequently a fuller description will be left until the petrographical chapter. For the present it will be enough to recognize among the original minerals, *i. e.*, those not produced by alteration:—

Feldspar, light colored, with light reddish or greenish tints due to alteration. Often on the cleavage faces fine parallel lines can be detected, and such feldspars contain less silica. The more siliceous feldspars are generally in shorter rectangles.

Quartz, often secondary, like glass and hard.

Augite, not easy to recognize and often altered, dark-colord. In the coarser basic, *i.e.*, less siliceous rocks augite is the main mass of what surrounds the feldspar. When there is a good deal of it, the feldspars lie in crystalline patches of it which when broken show a cleavage, and reflect the light in patches. This gives the lustre-mottled appearance characteristic of the Greenstone, and such rocks have been called ophites. In such cases, between the augite patches are more easily decomposed substances, and the consequence is that, on weathering, the surface of such a rock will have a peculiar pock-marked, lumpy look, which made Foster and Whitney call the rock "varioloid greenstone." Plate VII shows the general appearance of an exposure of this lustre-mottled rock, and a pocket lens will bring out the pock-marked appearance. The augite was often mistaken by early writers for hornblende. There is practically no hornblende visible in the Isle Royale rocks.

Olivine. Another mineral abundant in the Isle Royale rocks is olivine, which is hard to recognize in its fresh state, in fact hardly occurs fresh, but weathers into red micaceous specks which are easily noticed, and at other times changes into serpentine, a dark green substance. Iron ores may occasionally be recognized as black specks, generally magnetic with a black streak, *i. e.*, magnetite. Hematite gives the red color to many rocks; menaccanite has not been recognized with the naked eye. We must avoid a full description of all the minerals of alteration here, but shall refer to them in the chapter on petrography, Chapter VI., and shall merely remark here that, while the familiar epidote and calcite arid chlorite occur everywhere, analcite and datolite seem to be more common in the rocks that are not very augitic.

B. Variations in flows.

The lava flows vary decidedly in chemical character and in structure, not merely as between successive flows, but in different parts of the same flow, and some general account of these variations is necessary. Then, again, the flows are millions of years old, and have been more or less weathered and altered. This introduces a new class of variations.

(a) Variations between different flows.—As an example of the class of variations which appear on comparing different flows, we find in these lavas a great range in the amount of silica, some of the beds being quite acid, that is to say siliceous, others much less so. In a general way we may say for these rocks that the less silica a rock has (secondary impregnations not counted), the less likely it is to have white or light red, yellowish or light flesh- colored tints, and the more likely it is to have dark colors —grey, green, red or purplish. The less siliceous it is, the more readily fusible. Experiments show that this is true for the slags corresponding to lavas, and consequently the lavas which are less siliceous will solidify more slowly than the acid, and hence will spread out into more extensive sheets and be

coarser grained, for the same thickness of sheet. They are also heavier, and contain more; iron, lime and magnesia, and generally less of soda and potash. The bubbles formed by escaping gas, which when later filled with minerals are called amygdules, are likely to be larger and more clearly defined, and less like irregular pores.

Owing to the lack of a lustre-mottled texture and perhaps to their more rapid cooling, the less augitic rocks generally present a finer and more compact appearance, they break more cleanly, and with a smoother conchoidal fracture, and are more smoothly, abundantly and conspicuously jointed. The jointing often divides them into columns. The "ashbed" diabases, for example, indicate their relatively less augite in these ways even to the naked eye.

(b) Variations in the same flow.—Here we find great differences in texture and composition. Near the margin the flow is finer grained, the contrast being more marked in the basic flows. The crystals which began to form while it was still moving, especially the feldspar and the olivine, are conspicuously in contrast with the rest of the rock, in which the eye can recognize no grain, but which looks like glass or porcelain. These marginal forms might naturally be called fine grained porphyritic trap, to distinguish them from the central forms which are coarser and have not so marked a distinction between the crystals formed before and after the bed came to rest, and might be considered different flows, if one were not careful. Of course a thin flow may have only the marginal form.

Then again at the top of the flow there is usually a belt of rock known as amygdaloid, which was originally full of bubbles of gas. The places of these bubbles have since been filled in with various minerals, as such porous layers allowed freer percolation of water. These amygdaloid layers will naturally be more sharply defined at the top than at the bottom and are of such importance as the repositories of copper, that the mining man's record of a boring is generally of an alternation of amygdaloid and trap, with occasional sandstone or conglomerate. This statement applies to the Keweenaw Point records also. But in correlation, such a record is not sufficient, as sometimes small flows will be amygdaloidal throughout, and so a belt of amygdaloid may be merely the top of one flow, or may be several small flows; it is by no means always easy to tell which, even in the drill cores, for a section through the ropy top of a modern lava field would show some puzzling alternations, and, moreover, the amygdaloid beds being soft, are much ground away.

Furthermore a tendency shows itself distinctly, as for instance in the flow which occurs in drill hole No. VIII from 196 feet down, for the lighter feldspar to gather at the top (Ss. 15354 to 15358), and for the augite to be more abundant at the bottom, of the same bed. This tendency cannot show itself at the margins where the cooling is too quick for it, but in the larger flows there is often, about two- thirds of the way from the top, a streak which is quite poikilitic or lustre-mottled, whereas the top is quite feldspathic.

C. Classification. Volcanic rocks.

We may then, for the naked eye, divide the lavas according to their acidity, into

1. *Quartz porphyries*, with distinct hexagonal pyramids of primary quartz, which often give nearly square outlines, in a porcelain-like groundmass which is generally reddish and light colored. The fracture is clean and conchoidal, if there are not too many porphyritic crystals, and the jointing is abundant and smooth, breaking the rocks up into angular fragments.

2. *Felsites*, with groundmass as above, but with no porphyritic quartz, the porphyritic crystals, if any, being of feldspar. Curious rounded forms (spherulites; see Chapter VI) occur in the Minong upper bed (p. 18). The felsites may be divided into felsophyres, and felsophyrites or felsite porphyrites, according as the feldspar is unstriated or striated.

3. *Melaphyre porphyrites*, with much striated feldspar which generally appears more or less porphyritic, usually greenish, more rarely reddish; the flows have a strong tendency to fine grain, smooth fracture and well developed joints, arid are dark colored and frequently have conspicuous reddish specks of altered olivine; they tend to have a very scoriaceous upper surface, "ashbed," with red sedimentary fillings of clay, etc.; the amygdaloid pores are smaller and more irregular than in the more basic rocks, and less completely filled, the secondary zeolites which fill them being often analcite and datolite; chalcedony is common. These are the "ashbed" diabases of Pumpelly and very nearly the diabase porphyrites of Irving, but since I find as a general rule that altered olivine in large distinctly porphyritic crystals, altered to a red micaceous substance, is a pretty constant ingredient in these rocks, I presume Irving called this substance altered augite. This it would be very convenient to do from a systematic point of view, but the original mineral is certainly more often olivine. Moreover, this melaphyre porphyrite may occur in the same flow with more basic types next to be described, and in fact can hardly be distinguished from marginal forms of other, more basic flows, which are probably included among Irving's diabase porphyrites. But the melaphyre porphyrite is not quite so dark, nor so heavy.

4. *Melaphyre ophites*. These are the same as the lustre-mottled .melaphyre, varioloid greenstones, and olivinitic melaphyres and diabases of previous writers. But the olivine is a microscopic constitutent, even though the rocks are distinctly more basic than those of the preceding group. It was always abundantly present, but is only rarely visible to the naked eye. It is the crowding out of the olivine from the augite patches, which in a bright light often appear irregularly lustrous and make no objections to enclosing the feldspar,—that gives the characteristic mottled texture. The term ophite, in

allusion to the resemblance to the mottlings of a snake, is a short and convenient term originally applied by A. Michel Levy to similar French rocks, which I shall use interchangeably with mottled and lustre-mottled melaphyre.

5. *Melaphyre dolerite*. This is a term which I apply to certain parts of flows, rather than to indicate a certain basicity. Near the center of certain of the thicker flows are streaks of this texture, in which the coarse grained feldspar and augite are both well crystallized, in similar dimensions, and there appear to have been interstices between them which are now filled with chlorite.

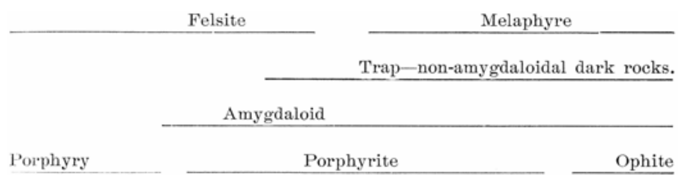
D. Sedimentary rocks.

We pass next to the sedimentary rocks of Isle Royale. These vary, according to their grain, from coarse conglomerates, so coarse that we can hardly tell if certain pebbles are not really lava flows, to red shales. The character of the fragments varies, from the angular fragments of the breccia bed, the irregular scoria of the "ashbed," e. g., down in drill hole No. IX, 279-291 feet, and the conchoidal angular fragments of the true volcanic glass ashes (S. 15236), to the rounded pebbles of the conglomerate bed, and the rounded grains of the sandstone. In general there is much more basic material in these beds, i. e., grains of augite and feldspar and pebbles of porphyrite and melaphyre, than we are wont to see in fragmental rocks, but on the other hand the proportion of basic material is less than that of basic lavas among the lava beds. This may be due to the greater durability of the acid rocks, or also it may be due to the fact that the acid lavas having been at the time of their protrusion more viscid than the basic, were more likely to pile themselves up, so as to be more exposed to attack by the waves. A deep red color is characteristic of all the sedimentaries, and as this color is due probably to oxidized iron from the associated igneous rocks, and to the fact that there was no vegetable matter to reduce the iron, it has more than accidental significance.

E. Field names of rocks.

Even in our detailed survey of the geological column as derived from the drill borings, which is planned to be intelligible for those who work only with the naked eye, I cannot deny that in many cases I have received aid from the microscope, but I have made only those distinctions, and used only those names which can, I believe, be used by the field observer, after he has had a little special acquaintance with the rocks. I do not wish to be understood as maintaining that the particular grouping and divisions that I have made here will be found sufficient or even as plain in some other region. There are a large number of rock names, beside those strictly technical ones, which can be applied only after a thorough investigation of a rock—names from which a selection must be made by the worker in the field, to express such important characters as he can observe in the field. As we have already said above, the very same flow may differ in many ways at its margin and at its center, and an ophite may be easily recognized as such in a thick flow, while in a thinner flow the same structure requires a microscope for its recognition, though even then there are often suggestive hints in the character of the decomposition, which may guide the experienced observer. In some other region perhaps, the presence or absence of olivine may be a feature upon which many other features depend, but in our rocks the altered olivine is more conspicuous, if not originally more abundant, in the porphyrites than in the ophites.

The field observer may in some cases be able distinctly to class a rock as ophite or something else, in other cases he cannot do so. In some cases he may be quite certain whether a given rock is a quartz porphyry, a quartzless porphyry, or a porphyrite (with predominant soda-lime feldspars), and in some cases he must fail. There are, indeed, flows which stand on the border lines, where only the most careful and systematic application of an arbitrary definition will put them into one class rather than into the other. For the field observer, therefore, it is necessary to have overlapping names which will cover such cases as these, and the following scheme, I believe, is sufficient for field use.



If a special term is needed for the coarser forms of basic rocks, dolerite is far preferable to diorite, and a proper gabbro does not appear in place on Isle Royale, so far as I know.

§ 2. Rocks south of the drill holes.

In giving the succession of the rocks, we shall begin at the top or youngest bed, as that is the way Marvine reckoned the Eagle River section on Keweenaw Point with which we wish to compare the Isle Royale section. That is the order, too, in which the beds are met and numbered in drilling, and in sinking shafts like the Tamarack, or in driving adits like the long one at the Copper Falls mine. In numbering and measuring, we shall call 0 the top of drill hole No. XI, where we have the highest trap observed. We may have traps indeed south of this, but probably not, as south of Cumberland Point no trap has been observed; nor south of Hay Bay, and hole No. XI lies on a line joining these points and considerably southeast of the line of strike of the extensive outcrops of conglomerate on Cumberland Point, between Grace Harbor and Rainbow Cove. According to the correlations here advocated there should at least be the horizon of the Lake Shore traps of Keweenaw Point to the south of hole No. XI, for it must be remembered that the beds farthest north on Keweenaw Point correspond to the beds farthest south on Isle Royale. The occurrence of beds on or near Isle Royale corresponding to the Lake Shore traps cannot be absolutely denied, for they may be under the waters of

Lake Superior, or may pass through the drift-covered stretch extending from Rainbow Cove to Siskowit Bay. But the Lake Shore traps are not, as I believe, persistent on Keweenaw Point, rapidly diminishing, and finally disappearing to the southwest, in harmony with a general law. Where they go inland south of Silver Creek, in T. 58, R. 32, they are much narrower than they are farther out on the point, and around Portage Lake no trace of them is found. Consequently we should not, in the absence of any confirmatory evidence, be justified in assuming that they spread to Isle Royale, especially as they represent the last effort of the volcanic activity.

The southeast shore of Isle Royale is lined with conglomerate and sandstone ledges, and is about 24,395 feet from the southeast corner of Sec. 27, T. 64, R. 38, in a direction S. 30° E., or (as drill hole No. VIII is 340 feet S. 30° E. from the same corner) 24,055 feet from No. VIII. Our conclusions as to the rocks that occupy the space between this southeast shore and drill hole No. XI must be largely hypothetical, both as to their thickness and as to their character, but it seems to me there is some reason to believe that a fault runs as indicated on the map, through the low land connecting Rainbow Cove, Lake Feldtmann, and Siskowit Bay. The reasons are as follows:

(1) There is a difference in the attitude of the conglomerate of the two sides of Rainbow Cove that indicates some disturbance between them. The end of the point at the southeast end of Rainbow Cove is made of coarse conglomerate with occasional layers of coarse sandstone, which has a dip of 8° to 9° almost due south. Imbedded pebbles of the traps, melaphyres, amygdaloids, and especially of a coarse porphyrite with large feldspar crystals in a dark base, are very numerous, continuing along the south side of lot 2, Sec. 30, T. 63, R. 39. Whereas on the other side of the cove, the point between Sec. 14 and Sec. 23, T. 63, R. 39, has a similar conglomerate, with dips; 10° to S. 30° E., 10°-12° to S. 20° E., 15° to S. 25° E., 13° to S. 25° E., 14° to S. 30° E., and the like. This indicates some disturbance between these two conglomerates. I have also thought of an unconformable overlap, or of a fault, the continuation of that coming down from the fault on Huginnin Cove, as the explanation of this.

(2) On the other end of this southernmost shore we have, across Point Houghton, dips averaging 20½° to the S. E., the formation being a rather uniform red sandstone, while a similar sandstone which occurs on Wright Island and on the other islands on the north side of Siskowit Bay, has dips of only 7°, 8°, 9°, etc. Now we find on the south side of Lake Superior suggestively similar relations between the dips,—say of the south trap range of the Ontonagon valley, and of the main range.

(3) The conglomerates of the point south of Rainbow Cove are continued in a ridge which runs south of Lake Feldtmann through Secs. 16 and 15, T. 63, R. 38. It looks very much as if* this ridge might be a repetition of the conglomerate belt which outcrops north of Rainbow Cove.

(4) Except by some such fault there is no accounting for the topography. There is nothing exceptionally resistant in the beds of Point Houghton, so far as one can see, which should enable them to withstand the preglacial erosion as a prominent ridge, and elsewhere on the island the rule is that the sandstones run in the valleys or underneath protecting trap. It will also be noticed in the Lake Survey soundings of Siskowit Bay, how quickly the water deepens to the northwest of the Siskowit islands, indicating an old valley there with a steep cliff (fault scarp?) on the southeast.

(5) Finally, such an assumed fault seems to be analogous to other faults of the island, as the one at Chippewa Harbor, p. 41 *et. seq*. We feel justified, therefore, in assuming its existence, though the uncertainty attending it is another good reason for taking our starting point on that side of it which is the more important, as any change in our views as to the fault will produce less change in our work. If we draw the fault through the low ground, as suggested, it will very nearly divide the territory between drill hole No. VIII and the lake shore into halves (distance taken as 11,860 feet). Then, assuming the dip of 12° 20', which is the dip found between No. X and No. IX, as the general dip, and it agrees well with the observations on .Rainbow Cove and Siskowit Bay, and subtracting 300 feet to allow for the greater altitude of drill hole No. VIII, which is 370 feet above the lake, we shall have (11,860 x .219=tan. 12° 20' = 2,584—300) about 2,300 feet of rock measured vertically above drill hole No. VIII, represented on the island. But, as we shall soon see, drill hole No. XI is 1,202 feet vertically above No. VIII, leaving us 1,098 feet of conglomerate and sandstone above No. XI. Applying a correction to reduce this vertical width to thickness perpendicular to the surface of the beds, we have 1,073 feet (1,098 x 0.977 = cos 12° 20'), say about 1,100 feet of sandstone on the north side of the fault, and about 2,600 feet of conglomerate and sandstone southeast of it, in each case with conglomerate at the base (12,200 feet x sin 12° 20' = 0.2136 = 2,606 feet).

How much of this section is repeated by the fault we do not know. On the point north of Rainbow Cove there is apparently over 600 feet of conglomerate exposed (3,000 feet x sin 12° 20' = 0.2136 = 641 feet). If this is the same conglomerate as that south of Lake Feldtmann, we may assume:

2,000 feet.	Red sandstone of Point Houghton, corresponding to the series found around Portage Lake from the old to the new Atlantic stamp mill (Sec. 34, T. 55, R. 34, to Sec. 20, T. 55, R. 35), and near the Portage Lake Ship Canal.
600 feet.	Conglomerate, with the cement often very calcareous, color prevailingly bright red, pebbles of all the range of lavas the melaphyres and porphyrites quite common, agate pebbles like the agate pebbles which occur in the Minong trap, not rare. This I take to represent both the "Outer" and the "Great" conglomerate of Keweenaw Point, the "Lake

Shore" trap not appearing.

§ 3. DRILL HOLE RECORD.

DRILL HOLE NO. XI.

Top of No. XI, dip assumed 12° 20'; cos dip=0.9763.

The reasons for the assumption of this dip will be stated when there shall have been enough of the column given to include the part for which a given dip is assumed, at which time the reasons can be given without anticipating facts. (See end of record of this drill hole.) The *vertical* width of the beds, i. e., along the drill holes, is given in feet in the left hand column without parentheses (N. B. not the *horizontal* width which Marvine gives), and under it in parentheses is given the true thickness as found by subtracting a correction equal to (vertical width) x (1-cos dip). In the main body of the text follow, next, numbers that denote the limits, in feet, of the several beds below the tops of their respective drill holes. Then follow, in parentheses, high numbers which refer to the thin-sections of rocks from the respective beds; collection of Michigan Geological Survey.

17+ 0-17; (Ss. 15544-5). **Ophite;** fine grained, massive, with red and white fine grained veins; lustre-mottlings visible. This is near Marvine's bed No. 7, Eagle River section.*

73 (71) 17-90; (Ss. 15546-63). **Conglomerate;** red with calcareous cement and a great variety of pebbles; the acid quartz porphyry predominates, but felsites, porphyrites and melaphyres are also present. Marvine's bed No. 8.

6 90-96; (Ss. 15565-6). **Melaphyre,** thin and amygdaloidal, with chloritic amygdules; slightly ophitic.

7 96-103; (Ss. 15567-8). **Melaphyre,** amygdaloidal. While not coarse enough, that is not thick enough flows to show the characteristic texture to the naked eye, the two small preceding beds appear to belong to the melaphyre ophites, with calcite, quartz and zeolite amygdules.

21 (20) 103-124; (Ss. 15569-72). **Melaphyre,** ophite. The upper 5 feet are amygdaloidal, and make, with the above two small flows, one amygdaloid belt.

0 A very thin **Sediment** with a calcareous cement underlies this bed.

13 124-137; (Ss. 15573-5). **Melaphyre,** amygdaloidal. Marvine's bed No. 16.

9 137-146; (Ss. 15576-9). **Conglomerate;** red, with the usual porphyry and felsite pebbles. Perhaps equivalent to Marvine's bed No. 17.

*Geol. Sur. of Mich., 1, Pt. 11, p. 120.

8 146-154; (Ss. 15582-3). **Porphyrite** (?), amygdaloidal. I think it not impossible that this is merely a boulder in the conglomerate, as we have the conglomerate again interrupted by something similar (S. 15585).

5 154-159; (S. 15584). **Conglomerate,** as above.

2 159-161; (S. 15585). **Porphyrite,** like S. 15583.

37 (36)

61 (59) 161-198; (Ss. 15586-99). **Conglomerate;** continued, growing finer and passing into red sandstone in the last 7 feet. It seems to me quite possible that we have in these last 59 feet only one bed of conglomerate which will correspond about to Marvine's bed No. 17, but his sandstones, Nos. 17, 19 and 21, are separated by single flows, and are more or less conglomeratic, and our conglomerate may represent the whole of them.

11 198-209; (Ss. 15600-4). **Melaphyre,** amygdaloidal.

3 209-212; (Ss. 15604?-5). **Melaphyre,** glassy; in contact with sediment; perhaps a surface coil of the trap next below.

10 212-222; (Ss. 15606-9). **Melaphyre,** ophite; amygdaloidal and feldspathic.

44 (43) 0 222-266; (Ss. 15610-19). **Melaphyre,** ophite; about 17 feet of amygdaloid at top and 9 feet at the bottom. Perhaps they are two minor flows. We have distinct **Sedimentary** matter in the parting at bottom.

9 266-275; (Ss. 15620-1). **Melaphyre,** amygdaloidal; from 272 to 275 the amygdules are not so prominent.

8 275-283; (Ss. 15622-3). **Melaphyre,** amygdaloidal; 2 feet amygdaloidal at top, the rest compact. It is really a fine grained ophite, as most of these beds are, but they are too thin for the structure to develop so as to be visible to the unaided eye.

19.5 18 283-302.5; (Ss. 15624-6). **Melaphyre,** amygdaloidal; the upper 9 feet amygdaloid, with *copper* (at 289 feet), prehnite and quartz.

2.5 (2) 302.5-305; (Ss. 15627-8). **Shale,** red, indurated; in vein-contact with trap. Dip measured on drill cores, 14°.

6 305-311; (Ss. 15629-33). **Conglomerate,** with pebbles of melaphyre as well as of felsite; toward the bottom fine-grained and epidotic. Dips measured on the cores, 18° and 14°.

8 This is about the same distance above the bed that we correlate with Marvine's bed No. 35, as Marvine's No. 21 is. The very fine and partly indurated character of Marvine's bed No. 21 matches our two feet of red shale.

16.5 311-327.5; (Ss. 15634-8). **Melaphyre,** ophite; amygdaloidal; is markedly amygdaloidal for about 4 feet, then mildly spotted—somewhat more so at the bottom. The contact with the con- glomerate dips 19°. If the overlying bed is the same as Marvine's No. 21, this may represent bed No. 22, which is -mentioned by Irving as a typical representative of his ordinary diabases.*

*Copper-Bearing Rocks of Lake Superior, Mon. V, U. S. Geol. Survey, 1883, p. 65.

16.5 (16) 327.5-344; (Ss. 15639-42). **Melaphyre,** ophite; amygdaloidal for the first 7 feet.

5 344-349; (Ss. 15643-4). **Melaphyre,** amygdaloidal.

13 349-362; (Ss. 15644-6). **Melaphyre,** ophite; about 7 feet at the top and 1 foot at the bottom are amygdaloidal.

8 362-370; (Ss. 15647-50). **Melaphyre,** ophite; about 3 feet at the top are amygdaloidal.

14 370-384; (Ss. 15651-5). **Melaphyre,** amygdaloidal; possibly two flows.

5 384-389; (Ss. 15656-7). **Melaphyre,** amygdaloidal.

7 389-396; (Ss. 15658-60). **Melaphyre,** amygdaloidal.

61 (59) 396-457; (Ss. 15661-8). **Melaphyre,** ophite; first 20 feet or more amygdaloidal, then a fine grained black trap, with the lustre- mottling showing somewhat.

1 457-458; (Ss. 15669-71). **Sandstone,** dark, basic; porphyry fragments not marked. This may represent Marvine's bed No. 26.

(24) 458-482; (Ss. 15671-6). **Melaphyre,** ophite; first 6 feet an amygdaloid with datolite, then a fine grained black trap, finally distinctly mottled. At the base there is a **sediment**. Compare Marvine's bed No. 27.

10 482-492; (Ss. 15677-9). **Melaphyre,** ophite; first 5 feet amygdaloidal; below that a fine grained trap, the bottom of the bed apparently gone.

1 492-493; (Ss. 15680-1). Seam of red **clay flucan,** perhaps marking a fault. A fault throwing the south side down, and hading to the south would make a gap which we could not detect (see p. 71, Fig. 5), but we may be reasonably sure that there is no fault which would lead to a repetition farther north of the beds we have already described, for these consist of a number of sandstones and conglomerates with thin basic melaphyres of the ophite type, whose texture is sometimes coarse enough to be recognized, and these we do not again encounter. After two more conglomerates, we come to a series of somewhat less augitic flows, with nonfelsitic conglomerates.

6 493-499; (Ss. 15683-99). **Conglomerate,** with porphyry, felsite, and trap pebbles, and calcareous cement; dip about 13°-14°.

1 499-500. **Clay;** another seam, which may indicate a fault. Thus, as the conglomerate may be bounded by possible fault planes above and below, we cannot be certain of its correlation, and it may be a repetition of some higher or lower conglomerate, but relatively to our general correlation it is nearly in the position of Marvine's No. 28.

7.5 (7) 500-507.5; (Ss. 15690-2). **Melaphyre,** amygdaloidal.

3.5 (3) 507.5-511; (S. 15693). **Amygdaloid;** may belong to the flow above or to that below.

14 511-525; (Ss. 15694-6). **Melaphyre,** ophite; more or less amygdaloidal, especially the first two feet.

Here we will pass for a moment from hole No. XI to hole No. X, to compare the two. Assuming that hole No. XI at 525 feet is equivalent to hole No. X at 113 feet, which will make a difference of 412 feet; adding the excess of altitude of No. X over No. XI (206.7 — 143 = 64 feet), makes 476 feet, and dividing by the distance between them, 2,191 feet, we have 0.218 as tan of dip: i. e., the dip is 12° 20'.

The rest of No. XI we correlate as follows:

Hole No. XI at 532 feet, contact, is equivalent to hole No. X at 123 feet; difference, 409 feet. Hole No. XI at 536 feet, contact, is equivalent to hole No. X at 133 feet; difference, 403 feet, and the characters of the beds assumed to be equivalent harmonize very well.

We are led to this correlation by the fact that we cannot match, in No. X, the conglomerate at 493 feet in No. XI, unless possibly at 469 feet, in No. X, and if we did that the adjacent beds, e. g., at 457 feet, would not correspond. Hence we must find a match for the first beds in No. X, i. e., at 109 feet (for the first 107 feet are in a surface deposit, old lake bottom, fine red sands and clays), below 493 feet in hole No. XI, and we come upon the one given above, which is the best we can find. Moreover, this match gives the same dip for the beds that we shall find later for the correlation from No. X to No. IX,—one that agrees pretty closely with the dips measured on the drill cores. If the correlation is good but the dip really 13°, it would mean that the rock of No. XI had been upthrown about 29 feet, in which case our column would be that much too long. But there is absolutely no indication of any faulting in either direction. If the dip is steeper than we assume and the two holes do not overlap at all, we have made the column too short.

(512)

DRILL HOLE NO. X.

10 113-123; (Ss. 15463-5). **Melaphyre.**

12 0 123-135; (Ss. 15466-9). **Melaphyre,** amygdaloidal; a trace of sand at lower contact.

13 135-148; (Ss. 15469-72). **Melaphyre,** amygdaloidal; more compact in the lower 4 feet.

21 (20) 148-169; (Ss. 15473-8). **Melaphyre,** ophite; upper 9 feet amygdaloidal, then more massive.

23 (22) 170-193; (Ss. 15478-88). **Conglomerate.**

(589) This conglomerate contains abundant acid pebbles, of porphyry and felsite, and of melaphyre as well. This bed I take to be the conglomerate opened by the Island mine, as the two have a similar lithological look or character, and lie nearly in line of strike from each other. The Island mine conglomerate runs about 500 feet south of the north quarter post of Sec. 29, T. 64, R. 37. and has a steep dip (from 19° to 25°), considering its position. Again, near Siskowit Lake. 50 steps north of the southwest corner of Sec. 26, T. 65, R. 36, and down to the corner, we find along the same line of strike a conglomerate which I take to be the same bed. So it continues on. being probably the same as that indicated by Foster and Whitney at the southwest corner of the head of Rock Harbor, on Sec. 5, T. 65, R. 34. I think, however, that it does not pass through to Conglomerate Bay, but like other beds in this vicinity veers a little to the north and goes through the trough of Rock Harbor. It is barely conceivable that, if we turn and go in the other direction, by the time we shall have come to Grace Harbor all the overlying traps will have run out, and that this conglomerate will have merged in the general conglomerate of Cumberland Point. This conglomerate in drill hole No. X differs from those above it in that it carries a greater proportion of basic pebbles, especially of the immediately underlying melaphyre porphyrites, but it differs still more decidedly from any conglomerate within the first thousand feet beneath it, in that it still contains a considerable proportion of felsitic debris — more perhaps at the Island mine than at the drill hole. This contrasted relation of the conglomerates above and below this horizon holds good, so far as the meagre facts indicate, for the corresponding beds at the other exposures above mentioned. All these exposures, moreover, lie on the southeast flank of a fairly continuous ridge which is principally made up of the rocks which we have described as melaphyre porphyrites, similar to the "ashbed" type of diabase. Northwest of this porphyrite ridge we find a still more continuous ridge, the "backbone" of the island, which is made up of coarsely lustre-mottled rocks—ophites. It will be noticed, from what we have said, that not only the sedimentaries but the eruptives change their character, above and below the conglomerate horizon which we are studying. Above it we have a series of thin flows, generally largely amygdaloidal, but when coarse enough showing the mottling of the ophites, and interstratified with them numerous beds of siliceous sedimentary rocks. Below it, as we shall see, the beds are in general thicker and more massive, and less augitic (porphyrites), and the interstratified sediments and amygdaloids resemble those which form the hanging of the Ashbed type.

Now we have on .Keweenaw Point at Eagle River and elsewhere a precisely similar series, only with the order from southeast to northwest reversed, but the stratigraphic order the same. I use mainly for comparison Marvine's Eagle River section, as I have been over and revised it arid have collected specimens from it expressly for this purpose. Beginning from the upper- most trap bed actually noted (Geol. Sur. of Mich. I, Pt. II, p. 112) Marvine counts ten sandstones in the first 2,300 feet of the section horizontally, (i. e., 1,272 feet thick; *loc. cit*, p. 124) to bed No. 35. This is the greater part of his series (c) which he however carries down somewhat farther to the first scoriaceous amygdaloid. In this part of the series the beds incline to be ophitic when at all thick, and the character of the formation generally matches the beds above the Island mine conglomerate. It will be noticed that for this part of the section we have on Isle Royale but half the thickness represented at Eagle River, the thickness to the bottom of the Island mine conglomerate being but 589 feet, but on the other hand we have six to eight of the ten conglomerates and sandstones.

Beginning with the flows immediately below Marvine's bed No. 35 and the Island mine conglomerate, we find a distinctly less augitic character in the flows as a whole, while the base of each flow remains somewhat ophitic in texture; we can recognize this change under Marvine's bed No. 35, in the Copper Falls adit, the Tamarack mine and elsewhere. In my reexamination of the Eagle River section I observed that the change really takes place there also at the point indicated. Then in all cases the first sedimentary bed we meet below the Island mine conglomerate, respectively below Marvine's bed No. 35, is distinctly of the Ashbed type, e. g., at 415 feet in No. X, Marvine's bed No. 44. Below this bed the traps are still less augitic, and they, together with their associated scoriaceous conglomerates, have in each case about the same thickness. Under this complex we find also, both on Isle Royale and on Keweenaw Point, the largest flow of the coarsest ophite that occurs anywhere in the series, the Greenstone. Now I am well aware of the danger of purely lithological correlations, but in view of the fact that beds of the series which we have been studying have been followed for a distance along Keweenaw Point equivalent to that across the lake, in view of the fact that a basic lava sheet of 200 feet, yes, in some places of 1,000 feet thickness may be expected to spread a great distance, with some uniformity of lithological character, in view of the general parallelism both in sedimentaries and in traps, both above and below, there seems to be no reasonable doubt that the Island mine conglomerate is equivalent to Marvine's bed No. 35, or is, at least, at very nearly the same horizon.

I put in this last clause because if anyone should object that Marvine's No. 35 might have faded out and that another conglomerate might have formed on the Island at nearly the same point in the series, my arguments would not conflict with this hypothesis. As a matter of fact, however, the indications are that the bed we have just discussed is identical with Marvine's No. 35.

113 (110) 193-306; (Ss. 15489-501). **Melaphyre,** porphyrite. This is a pseudamygdaloid for the first 20 feet, that is, the amygdules are indistinguishable from decomposition spots. It is different from the ophites above, most markedly in microscopic characters, but also to the naked eye, for the feldspar is much more conspicuous and there is no lustre-mottling, as there would be very plainly in a bed of ophite of equal thickness. In other words the feldspar is large in proportion to the size of the augite. Light greenish seams and spots, and a generally lighter, more grayish green color may be noted on comparison. This would correspond to Marvine's bed No. 36.

It will be noticed in Marvine's description of bed No. 36 that the scoriaceous character of the amygdaloid is mentioned, which is characteristic of the less augitic melaphyres. Farther details as to the change in character must be left to the petrographic chapter. The feldspar is oligoclase instead of labradorite.

16 306-322; (Ss. 15502-5). **Amygdaloid.** This is a fine grained red amygdaloid, apparently the same kind of rock as the bed above, but a thinner flow.

0? Among the drillings at 321 feet were 2 inches; at 322 feet, 4 inches; at 323.3 feet, ½ inch of a basic **sandstone**. The driller's record threw no light on the occurrences, but from the gradually finer grain of the traps above and below them, I am led to believe that they all really belong at 322 feet, and that there is a bed of fine grained dark red basic sandstone there. Dip 14°.

3 (718) 322-325; (S. 15506). Perhaps another bed of Amygdaloid. At 325 a narrow seam is noted which may however be a fault.

7 325-332; (Ss. 15508-8). **Amygdaloid;** at 332 feet highly amygdaloidal, brecciated, and mixed with liner grained sediment; quite likely a slip.

6 332-338; (Ss. 15508-12). **Amygdaloid.**

77 (75) 338-415; (Ss. 15513-24). **Melaphyre;** of the porphyrite type at the top, but becoming darker and approaching the ophite type at the bottom. It is somewhat amygdaloidal down as far as 352 feet, beginning as a fine grained red porphyrite with amygdules of chlorite and a few of agate at the top. At 344 feet and 377 feet green rock was cut which would in the field prove, I feel sure, to be either rounded masses or irregular skeins, which are characteristic of this group, and are slightly more likely to be amygdaloidal than the adjacent rock. They are more decomposed, though this decomposition doubtless follows some primary feature, and are permeated with cavities lined with crystals of quartz and chlorite.

As we get toward the bottom the rock, which is firm and compact, and yields long drill cores, becomes darker, and finally somewhat lustre-mottled. *Copper* appears in paper-like sheets in the chlorite seams. This is probably Marvine's bed No. 43. Analyses of this bed will be found in Chapter IX.

(806)

11 (817) 415-426; (Ss. 15525-30). **Conglomerate.** This bed is the first of the scoriaceous conglomerates, otherwise known as ashbeds or scoriaceous amygdaloids. The matrix is very dark, of a deep maroon shade, generally speaking, very fine grained and argillaceous, and the pebbles are irregular masses of amygdaloid, like the beds with which they are associated. The line between the conglomerate and the underlying amygdaloid is extremely difficult to draw. This is the reason why these scoriaceous beds have been considered as extreme forms of amygdaloid, but there is no doubt that in the beds which I am now considering there is a large amount of detrital matter, almost exclusively from basic rocks. They are very calcareous.

This conglomerate corresponds very nicely to Marvine's bed No. 44—as well, indeed, as his bed No. 35 corresponds to the Island mine conglomerate. The underlying rock corresponds to Marvine's bed No. 45, being a melaphyre porphyrite, with a clean conchoidal fracture, as we shall see, and the immediately overlying bed is in each case indistinctly mottled. Marvine allowed eight beds between No. 35 and No. 44, but two numbers were allowed for beds unobserved, and none of the observations showed that Nos. 42 and 43 were separate beds, and in fact I inferred from the coarseness of grain and other things that in reality from No, 39 down to No. 43 was all one large flow (184 feet) corresponding so closely to our melaphyre in No. X (338-415, i. e.. 75 feet thick) as probably to be the same flow. That left four beds in the Eagle River section, between No. 35 and No. 44, to correspond to our six beds, in each case with a thick flow at the base. From the top of Marvine's bed No. 35 to the top of his bed No. 44 is, according to Marvine, 273 feet. The corresponding distance in our column of rocks is (806-567) 239 feet, which is quite as close a correspondence to the general ratios (see table at the close of this chapter) as could be expected, 50 miles away, and eminently satisfactory. The correlation is made much stronger by the study, under the microscope, in Chap. VI, of the comparative coarseness of grain, and the change in the character of the feldspar.

57 (56) 426-483; (Ss. 15531-7). **Melaphyre,** porphyrite. This is one of the most acid of the melaphyres, really of the type of an olivinitic augite andesite. The smoother fracture, generally lighter, green color, abundance of not very large white porphyritic feldspar aggregates, and compact texture are well marked. This is the bed that we seem to find at the top of drill hole No. IX.

(874)

We assume that No. X, 483 feet, is equivalent to No. IX, 49 feet, a difference of 434 feet. Subtracting the excess of altitude of No. X over No. IX (206.7-202.5*), 4.2 feet, we have 430 feet, which divided by the distance between them along the line of cross-section, 1973 feet, gives 0.217, the tan 12° 20'. This is the same as we had before, the two computations confirming each other and strengthening our correlations, which were in the first place purely lithological. In case this correlation is wrong, so that No. X and No. IX do not overlap, the resemblance noted being that of similar successive flows, we should have a steeper dip, or a fault. The correlation with the next hole north will give us a slightly steeper dip, about 13°. But a slight flattening of the dip going south is to be expected, and there is no reason at all to assume a fault. A fault the other way, producing a repetition of beds and leading us to exaggerate our column, is ruled out by the fact that the conglomerate, 415-426 feet in No. X, can be matched even approximately only at about 313-338 feet in No. IX, in which case we should expect to be able to match all of No. X and No. 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*.

*The altitude of the surface is 232.5 feet, but the 30 feet of drift material first encountered were omitted in reckoning the drill hole depths.

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 (53) 49-103; (30 feet of drift not counted) (Ss. 15390-7); corresponds to 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 (48) 103-152; (Ss. 15398-402). **Melaphyre,** porphyrite; to the naked 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 decomposed green, light colored spots, as in No. X, 344 feet.

(993)

44 (43) 170-214; (Ss. 15407-8). **Melaphyre,** porphyrite; not very acid; 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 (43) (1,100) 235-279; (Ss. 15413-6). **Melaphyre;** more or less amygdaloidal, with laumonite and datolite.

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 scoriæ. It is much decomposed. Marvine's bed No. 63? Dips on drill cores 25°, 23°, with signs of cross-bedding.

(1,112)

22 (21) 291-313; (Ss. 15425-9). **Amygdaloid.** Some of the specimens 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" *par excellence*.

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 (56) 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 *copper* 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 copper; at 420 feet a datolite vein; at 430 feet a brecciated amygdaloid. Therefore the last supposition seems most probable—that there is a fault.

(1,202)

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 along the section (2,218 feet), we shall have 0.231, i. e., tan 13°, about half a degree steeper than the dips we have computed thus far in our section south of this point, but the same as dips computed at points further north (p. 71). On the other hand the deeper of the two correlations, 427 feet in No. IX with 196 feet in No. VIII, would give us 0.183 as the tan of 10° 20'. This is much flatter than anything we have reason to expect, and the inference is that the fault affects this correlation rather than the other. Thus we are led to the conclusion that if there is a fault it cuts No. IX, raising the lower part of it but not the upper. Hence it is a normal fault with northerly or westerly hade. Fig. 8 may represent it.

The indicated vertical upthrow of the lower side is 107 feet. Such a fault as we see from Fig. 8, if it came between the top of No. IX and its correlate in No. X, would there make a dip too flat. Hence the dip of 12° 20', found above for the strata between No. IX and No. X, would have to be increased to 15° 10'. While, however, the dip might well be a little steeper, we should not expect it to be as much as that. Nor can we readjust the correlation of No. X and No. IX, as it is too marked in petrographic character. We may of course imagine another fault with hade to south that has thrown the bottom of No. X back into position, of which fault there is, however, not the slightest direct evidence, or we may suppose in spite of the evidence of the dips that the flatter dip is the true one, and that, as explained on page 36, the fault hades south. It is, however, possible to imagine a fault such in strike that it will leave No. VIII, No. IX and No. X in undisturbed relation to each other at the top, and yet gouge out a piece of No. IX low down, having either very nearly the strike N. 45° W. or else having a very flat dip.

The matches on which this argument is founded seem, microscopic evidence and all things considered, to be the only ones possible, especially because No. VIII, 47 feet, cannot find a match in anything lower than No. IX, 385 feet. No. IX, 427 feet, should certainly appear in No. VIII, but cannot find a match nearer the surface than No. VIII, 196 feet.

A fault such as the one we are describing would not affect our record, however, as we are now about to pass from No. IX, 385 feet, to No. VIII, for it would cut No. IX below this point.

According to our correlation, the distance from the bottom of the bed corresponding to Marvine's No. 43, to the bottom of the bed corresponding to his No. 65, is (1202-806) 396 feet, while the corresponding distance in the Eagle River section is 573 feet—thicker in about the usual ratio, i. e. about 3:2. (See the end of this chapter.)

DRILL HOLE NO. VIII.

24 (22) 47-71; (Ss. 15335-7). **Melaphyre;** the top 13 feet amygdaloidal; intermediate type between ophite and porphyrite, not markedly belonging to any subdivision of the melaphyres; like the flows just below. It is correlated with and just about the size of No. IX, 385-418.

(1,224)

18 71-89; (Ss. 15338-9) **Melaphyre,** fine grained and amygdaloidal. In No. IX the records are much mixed along here. There are slide or flow contacts at 408 feet, 413 feet, 421 feet, with fine-grained, red, chloritic, datolitic and prehnitic amygdaloids. Here is where I have supposed that the fault above discussed goes through.

14 89-103; (Ss. 15340-1). **Melaphyre,** amygdaloidal.

32 (31) 103-135; (Ss. 15342-4). **Melaphyre,** amygdaloidal.

11 135-146; (Ss. 15345-7). **Melaphyre,** amygdaloidal.

18 146-164; (Ss. 15348-9). **Melaphyre,** amygdaloidal.

32 (31) 164-196; (Ss. 15350-3). **Melaphyre,** amygdaloidal, perhaps largely pseudamygdules, of laumonite, chlorite and prehnite.

The flows above are all of moderate size and, though varying somewhat, have the general habit of the less augitic melaphyres, i. e., the melaphyre porphyrites. The microscope shows that they carry oligoclase feldspar.

(1,347)

77 (75) (1,422) 196-273; (Ss. 15354-8). **Melaphyre,** ophite. This bed for 3 feet is very amygdaloidal, then coarser, with occasional chloritic amygdules, and becoming still coarser it shows the rusty specks of micaceous altered olivine; toward the base it is fine grained with datolite veins. This matches very closely No. IX, 427-468, which is so coarse when the hole ends that the latter evidently stops in the middle of the flow.

57 (56) 273-330; (Ss. 15359-64). **Melaphyre,** ophite; like the flow above.

32 (31) 330-362; (Ss. 15365-6). **Melaphyre.**

15 362-377; (Ss. 15367-8). **Melaphyre.**

The above four flows steadily increasing in their relative thickness toward the top flow, seem to belong to the same type. Though belonging to the ophites rather than to the porphyrites. they have peculiar microscopic characters of their own, and are not very ophitic.

(1,524)

42 (41) 377-419; (Ss. 15369-73). **Sandstone;** red, with 1 foot of conglomerate at the bottom; in general quite uniform in grain; dark chocolate red; sometimes brecciated, with small red veins; the conglomerate at the base contains some felsitic debris.

Dips measured on drill cores 13°, 14½°, 15°, 16°, 15°; cross-bedding of 23°. It is noticeable that the dips thus obtained from drill 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 laminæ 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.

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 1,589 440-444; (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.

42 (41) 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° 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.

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

DRILL HOLE NO. VII.

73 (71) 10?-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.

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 (20) 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.

0 At 130 seam of **sedimentary** matter; much prehnite.

32 (31) 130-162; (Ss. 15295-6). **Porphyrite,** amygdaloidal, as above; at 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 possible 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 (79) 221-302; (Ss. 15306-15) **Melaphyre;** intermediate type, quite 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 (21) 302-324; (S. 15316). **Amygdaloid.**

0 324; (S. 15317). **Vein** (possibly fault or contact); carries *copper* crystals, prehnite and quartz.

13 324-337. **Amygdaloid.**

0 (1,948) 337; (S. 15319). Vein and perhaps contact; carries *copper*, etc.

38 (37) 337-375; (Ss. 15318-20). **Porphyrite,** amygdaloidal; fine grained 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 (28) 394-423; (Ss. 15321-4). **Melaphyre;** intermediate form, more 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÷1848, i. e., 0.231 = tan 13°, 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).

33 (32) (2,077) 91-124; (Ss. 15243-7). **Ophite.**

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° 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 (70) 64-136; (Ss. 15072-5). **Melaphyre,** ophite.

0 (2,532) 136; (S. 15075). **Sedimentary** seam.

39 (38) 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?

(2,570)

39 (38) 175-214; (Ss. 15080-2). **Melaphyre,** ophite. There is some doubt whether this is not one flow with the underlying.

57 (56) 214-271; (Ss. 15083-5). **Melaphyre,** ophite; about 9 feet coarsely amygdaloidal at the top, and 1 foot at the bottom.

54 (53) 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.

40 (39) 325-365; (Ss. 15087-8). **Amygdaloids;** probably more flows than one; base ill-defined.

73 (71) 365-438; (Ss. 15089-91). **Melaphyre,** ophite; amygdaloidal at top, grey, and apparently not very basic.

37 (36) 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?)

81 (79) (2,942) 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*.

14 556-570; (Ss. 15098-9). **Amygdaloid,** brecciated.

30 (29) 570-600 (?). **Melaphyre,** ophite (?); amygdaloidal; core about half ground away.

31 (30) 600-631; (Ss. 15100-1). **Melaphyre,** ophite.

19 631-650; (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.

(3,034)

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° 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 (32) From No. II, 650 feet (Ss. 15103-7).

40 (39) to No. IV, 40 feet (Ss. 15155-7). **Melaphyre,** ophite.

(71)

68 (66) 40-108; (Ss. 15158-60). **Melaphyre,** ophite; about 9 feet of amygdaloid at top, with calcite and chlorite.

0 108; (S. 15161). **Sediment,** basic; to the naked eye like a fine grained amygdaloid.

25 (24) 108-133; (Ss. 15162-3). **Melaphyre,** ophite; fine grained; at 122 feet, fissure with quartz crystals.

2 (3,197) 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.

92 (90) 135-227; (Ss. 15165-8). **Melaphyre,** ophite; very ferruginous.

18 227-245; (Ss. 15168-9). **Amygdaloid,** brecciated.

18 245-263; (Ss. 15170-1). **Amygdaloid.**

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

24 (23) 280-304; (S. 15173). **Amygdaloid.**

(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.

120 (117) 304-424; (Ss. 15174-83). **Melaphyre,** ophite.

(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 (3,506) 434-450; (Ss. 15187-8). **Amygdaloid;** porphyritic texture, which is common in the other amygdaloids, with *copper*, laumonite and prehnite.

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 844 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 X 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 feet x 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.

(3,656) This corresponds very nearly to a dip of 14° 20', which is what we have by correlation of No. I and No. Ill, p. 84.

63 (61) 0-63; (Ss. 15001-4). **Melaphyre,** ophite; mottled feldspathic and slightly amygdaloidal.

90 (87) 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 (72) 153-227; (Ss. 15011-6). **Melaphyre,** ophite; amygdaloidal the first 10 feet, which character fades out in the next 9 feet; chlorite and calcite amygdules and veins.

48 (46) 227-275; (Ss. 15017-20). **Melaphyre,** ophite; 5 feet of amygdaloid at top, with a little *copper*.

23 (22) 275-298; (Ss. 15021-5). **Melaphyre;** fine grained, somewhat ophitic, amygdaloidal for 4 feet at top and 3 feet at bottom; with prehnite, calcite and laumonite.

64 (62) 298-362; (Ss. 15026-37). **Melaphyre,** ophite; amygdaloidal for 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. Ill 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. Ill to 44-59 feet.

9 377-386; (Ss. 15040-1). **Melaphyre,** amygdaloidal. Equivalent in drill hole No. Ill to 59-67 feet.

39 (38) 386-426; (Ss. 15041-5). Fine grained amygdaloids and scoriaceous beds with basic sediment mixed and at the bottom. This is equivalent to the beds No. Ill, 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 (29) (4,097) 426-456; (Ss. 15045-50). Minong **Porphyrite;** equivalent to No. III, 100-134 feet. This is quite acid, probably not belonging to the melaphyres at all, but rather a felsite porphyrite. No olivine can be recognized in it with certainty, either microscopically 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 distinguish 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 Kearsarge 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 intervening 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 $^{3}/_{5}$ $^{9}/_{7}$ $^{6}/_{3}$, 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 (77) 456-536; (Ss. 15051-5). **Melaphyre,** porphyrite, the "Minong trap;" equivalent to No. Ill, 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. Ill) is nearly 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. Ill, 215 feet., i. e., 321 feet higher. Adding the excess of elevation of No. Ill 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° 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. Ill and No. XIII. Stockly's observations, using the outcrop at the surface near tunnel No. 5, made the dip a little less

(14¼°), but only a fraction of a degree. There is no indication of a fault either wav between No. I and No. Ill, and there is no possibility of much of a fault.

(4,174)

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

DRILL HOLE NO. III.

94 (91)	215-309; (Ss. 15123-8). **Melaphyre,** ophite; equivalent to No. I, 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)	
30 (29)	309-339; (Ss. 15130-3). **Melaphyre,** amygdaloidal. Veined and seamed; very feldspathic; corresponds to No. I, 630-662 feet. (S. 15064).
24 (23)	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.
(4,317)	
47 (45)	363-410; (Ss. 15135-8). **Ophite,** amygdaloidal; possibly two flows, separated at 380 feet.
43 (42)	410-453; (Ss. 15139-42). **Melaphyre,** ophite.
20 (19)	453-473; (Ss. 15143-4). **Melaphyre,** feldspathic.
89 (86)	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.
(4,509)	

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. XIIIA, 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. Ill, 215 feet), than the tunnel is from drill hole No. I. The distance from No. Ill to No. XIII is 1775 feet and the top of No. Ill is (231-216) 15 feet the lower. Hence, allowing the dip slope to be 1:4 (tan 14½°) 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. XIIIA for this part of our section. In hole No. XIII the rock grows less amygdaloidal after the first 17 feet and in hole No. XIIIA 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. XIIIA (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. Ill, 453 feet, then the first 17 to 25 feet of amygdaloidal rock will correspond to a point in No. Ill, down about 473 feet. Then for the bottom contact of the big ophite next below, at No. Ill, 562 feet, our first match will be No. XIII, 125 feet, and No. XIIIA (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. Ill, 1,775 feet, is 0.238, or tan 13° 20'; 562-93 + difference in altitude (216-231) is 454, divided by distance at right angles to strike, from No. XIII to No. Ill, 1,775 feet, is 0.256, or tan 14° 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. Ill was determined (p. 84) with the aid of No. 5 tunnel, as 14° 15'. It is therefore probable that the lower part of No. XIIIA is more nearly in undisturbed relations with No. Ill, 562 feet, than is No. XIII, though the dip may be steeper than thus indicated. Then the fault which cuts No. XIIIA at 86 feet must separate No. Ill, 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. Ill, 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. Ill is undisturbed, i. e., that (1775 X 0.256 = 454 + 15) No. XIII, 0 feet, is equivalent to No. Ill, 468 feet, is much better. If we accept this correlation, we must imagine that the fissure vein which crossed No. XIIIA crosses No. Ill also, probably being the vein entering at No. Ill, 497 feet, and throwing the part above up. Now drill holes Nos. XII, XIV, XIII, tunnel No. 5 and drill holes Nos. Ill 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. Ill, but cutting into No. Ill 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. XIIIA. Let B be the point where the fault cuts hole No. XIIIA (86 feet), and C a point at the same level in No. XIII (86 X tan 45°, 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 ∠CDB is CB/CD, i. e., $^{61}/_{191}$. 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 ∠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 ∠FCN is 90° plus ∠FCD, which latter is equal to the 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 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. Ill, 473-562, and a corresponding amount out of No. Ill 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 numbers referring to XIIIA with a v. before them are the distances reduced to the vertical by multiplying by sin. 45°, i. e., 0.7071.

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

DRILL HOLE NO. XIII.

(4,509)	
1	125-126; (S. 15722). **Sandstone,** basic and red.
58 (56)	126-184; (Ss. 15723-41). **Melaphyre,** ophite.
45 (43)	184-229; (Ss. 15742-5). **Melaphyre,** feldspathic ophite.
1	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 (21)	230-252; (Ss. 15747-51). **Melaphyre,** amygdaloidal, fine grained; red, with clay veins from the top and the bottom; brecciated and prehnitic. Seems to be of the porphyrite type.
90 (87)	252-342; (Ss. 15752-61). **Melaphyre,** ophite; feldspathic.
7	342-349; (Ss. 15761-2). **Melaphyre,** amygdaloidal.
10 (4,735)	349-359. (S. 15763). **Melaphyre,** amygdaloidal; prehnitic.
88.5 (86)	359-447.5; (Ss. 15764-72). **Melaphyre,** ophite; amygdaloidal for 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 X tan 14° 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° 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,

45.5 but there is no reason to think that there is any
(44) fault and every reason to believe that this is
(4,865) 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.

DRILL HOLE NO. XIV.

116 22-138; (Ss. 15780-9). **Melaphyre,** porphyrite:
(111) the last 10 feet of 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;
(58) feldspathic, first 9 feet amygdaloidal; toward the bottom, veins with prehnite and *copper.*

2 200-202; (S. 15798). **Sandstone,** basic; with amygdaloidal fragments. 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;
(159) amygdaloidal the 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
(67) porphyrite. This very marked and peculiar bed has a fine grained red groundmass, in which are large crystals of whitish feldspar, frequently 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 independent flow. The prehnite and copper veins and laumonite seams occur throughout the bed to the bottom. This porphyrite 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
(5,264) microscope shows conchoidal glass forms in this rock.

165 440-605; (Ss. 15821-34). **Melaphyre,** ophite.
(158) This big flow rivals the "backbone"
(5,423) 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 porphyrite 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° 40', the beds at the lake shore (1,300 feet X 0.300 = 390 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 X 0.325 + 198 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 southeast. 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.**

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.

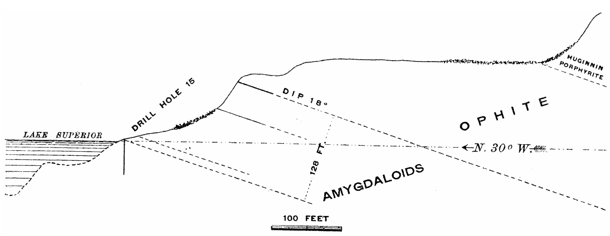


Fig. 12

Figure 12. Cross-section near drill hole No. XV.

DRILL HOLE NO. XVI.

39 (38) 0-39; (Ss. 15835-7). **Melaphyre,** ophite; chloritic amygdules at top of bed.

15 (14) 39-54; (Ss. 15838-40). **Melaphyre;** streak of green prehnitic amygdaloid at top.

27 (26) 54-81; (Ss. 15840-2). **Melaphyre;** red and amygdaloidal for the first 6 to 8 feet, with calcite and laumonite (?) in amygdules.

33 (31) 81-114; (Ss. 15843-7). **Melaphyre,** amygdaloidal; at the top the 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 much broken and shattered and appears amygdaloidal.

5,532

40 (38) 114-153.5; (Ss. 15848-50). **Melaphyre,** feldspathic; intermediate between porphyrite and ophite.

11 (11) 153.5-165; (Ss. 15851-3). **Melaphyre,** amygdaloidal; at the top there is a green decomposed seam; laumonitic amygdules.

9 165-174; (Ss. 15854-5). **Melaphyre,** amygdaloidal.

12 (11) 174-186; (S. 15856). **Amygdaloid.**

15 (14) 186-201; (Ss. 15857-8). **Melaphyre,** amygdaloidal; at 201 feet there is a decomposed green seam, which may be a vein or a decomposed margin between two flows.

25 (24) 201-226; (Ss. 15859-62). **Melaphyre,** amygdaloidal. All the above series of amygdaloidal melaphyres are small flows of the ophite type.

32 (30) 226-258; (Ss. 15863-7). **Melaphyre,** feldspathic.

17 (16) 258-275; (S. 15868). **Melaphyre.**

22 (21) 275-297; (Ss. 15869-71). **Melaphyre,** amygdaloidal.

23 (22) 297-320; (Ss. 15872-3). **Melaphyre,** ophite; amygdaloidal.

28 (27) 320-348; (Ss. 15874-7). **Melaphyre,** ophite; vesicular and amygdaloidal, with laumonite, for the first 13 feet.

43 (41) 348-391; (Ss. 15878-82). **Melaphyre,** ophite.

19 (18) 391-410; (Ss. 15882-4). **Melaphyre,** amygdaloidal.

28 (27) 410-438; (Ss. 15885-7). **Melaphyre,** ophite.

10 438-447; (Ss. 15888-96). **Breccia** or **Scoriaceous Conglomerate**; a mixture of fine grained sandstone and of a porphyrite like the Huginnin porphyrite.

5,849

From this point we shall take off 0.06 to reduce from **vertical** *width to* **thickness***, implying a dip of about 20°.*

20 (19) 455-475; (Ss. 15897-8). **Porphyrite;** like the Huginnin porphyrite. No. XIV, 367-436 feet.

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.

124 (117) 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.
(5,996)

7 (6,003) 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°.*

46 (42) 618-663.5; (Ss. 15924-8). **Porphyrite.**

33 (30) 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°.

89 (80) (6,155) 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°.

124 (112) 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.

90+ (80) 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.

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

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.
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.

(53) 843-1054; specimen from the bottom showed
6,400 that the drill was still in the felsite. This adds some fifty feet to the section given.

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.
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 Marvine, 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° 40', whose sine is 0.218. Thus if we had made the average dip 14° 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° 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., Marvine'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 Marvine'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 Marvine's figures, but on his map he unites the next group, the Ashbed group, with this as No. 5. The next group, still following Marvine'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 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 overestimated 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.

*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.

§ 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 thick- ness 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, Tight 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				2600	2500						
First known trap	Marvine's (c).	XI	0	0	No.1						Temperance River group?
Small ophites, numerous sandstones											
Island mine conglomerate		X	170 193	567 589	35	1146	1035 1012	2146	18?		
Transition flows, porphyrite and ophite											
Scoriaceous conglomerate	Marvine's (b).	X	415 426	806 817	44	1417	745	2021	17		
Green porphyrites		IX	279 291	1100 1112	63 65	1810	368	1639	17	853 885	
Scoriaceous conglomerate—"Ashbed"						2035	160 †0‡				
Porphyrites	Marvine's (c).	VIII	377 419	1526 1567	80?	2432 2496	495 500	1081 1053	16	1435 1445	
Red sandstone											
Porphyrites, etc.											
Felsite tuff		(VII) VI	81 91	2035 2045				160	*		Beaver Bay group?
Ophite, and the thickest ophite—the Greenstone		VI			90 108	2840 4120	Centr'l mine.				
Conglomerates—the Allouez or "Slide"		VI	363 386	2310 2332			0†	†0‡	15	2345 2378	Agate River group?
Amygdaloids mainly and thin ophites		II	136 175	2570?			660		14		
		IV (V)	133	3197			1474	1309	13 12		
Minong breccia		I	386	4030	"Kingston"					4853	
Minong porphyrite		(III)	426	4068	or		2599	2239	11	4873	
Minong trap			456 536	4097 4174	Kearsarge?						
Various beds ending with a thick ophite		XIII A									
Huginnin porphyrite		XIV	367 436	5194 5260							
Ophites											
Felsitic conglomerate		XVI	475 487	5868 5879					6	7643	
Various igneous flows and conglomerates											
Felsitic conglomerate and felsite tuff			786 910	6155 6267							
Felsite		XII		6400	Praysville.						

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

Table 4. Correlations between Isle Royale and Keweenaw Point.

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 amygdule, 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 bow 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 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 interval 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.

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

§ 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 is how 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 2 w) 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 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.

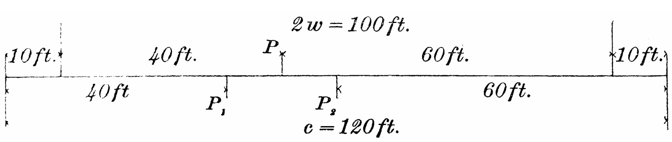


Figure 13. Illustrates the relation of a sheet one hundred feet thick, having a ten-foot contact zone on each side, to a sheet one hundred and twenty feet thick, whose walls are supposed to remain at a fixed temperature. From these data the temperature of the former sheet may be deduced.

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÷14,400, *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 240°, and subtracting 84° = 162°, 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 formulae (see appendix to this chapter), and we have given above only a popular resume. 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:

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

Of this a particular solution is:

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

e is the logarithmic base = 2.718282.

By varying x and 1 (x and 1 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 o 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) $u_0 = f(x)$.

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

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

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) $u_o = 0$ for x less than m — w or greater than m + w.

Moreover, for the sake of abbreviation we will write—

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

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 (1) 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.,

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

Now if the temperature of the sheet is uniform at the start, u_o, and therefore f (1), will be a constant between the limits indicated, and the integration can be easily performed. We shall have to change dl to d (nπl/c), which we may do if we divide the rest of the equation by nπ/c. Moreover, f (1) 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 · dy, where y is nπl/c. The integral is known to be (-cos y), that is -cos (nπl/c), and replacing 1 by the limits of integration,, we have the expression

-cos (n π (m + w) /c) -(-cos (n π (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) cos (x + y) - cos (x — y) = -2 sin x, sin y.

It is thus transformed into

2 sin (n π m /c). sin (n π w/c)

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

$$(9)\quad u = \frac{4}{\pi} u_o \sum_{n=1}^{n=\infty} \sin (n \pi m/c). \sin (n \pi w/c). \sin (n \pi x/c). \frac{q^{n^2}}{n}$$

an equation particularly easy to remember from its symmetrical relations with regard to x, m and w. It is obvious, as u_o 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.

How 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

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

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

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

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) π/4. u/u_o = sin (π m/c). sin (π x/c). sin (π w/c). 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 — o 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) π/4. u_0 = sin (π m/c). sin (π x/c). sin (π w/c).q. $D_u t$. (— (π 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) 1/u = — (π 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) $m = c/2$.

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 π m/c) sin (n π w/c) sin (n π 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 π/2) sin (n w/c) sin (n π (z + c/2) /c)

(16) $z = x — m = x — c/2$.

Now by Chauvenet's Trigonometry (36) from sin (n π /2) sin [n π (z/c + ½)] we get sin (n π z/c). ½ sin (n π) (and this is 0 for all whole values of n which alone need to be considered) + (cos. (n π z/c) $\sin^2$n π/2.

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

$$(17)\quad u = \frac{4}{\pi} . u_o \sum_{n=1}^{n=\infty} \sin^2\left(n\frac{\pi}{2}\right)\left(1/2\left(\sin\left[(n\,\pi/c)(w+z)\right] + \sin\left[(n\,\pi/c)(w-z)\right]\right)\frac{q^{n^2}}{n}\right)$$

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. 48). It is to be remarked that if w — z is itself negative, we must consider $u_{w—z}$ as negative, i. e.

$$u_{w-z} = -u_{z-w}$$

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 π /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) $\log. q = -\pi^2 a^2 c^{-2} t$

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 abscissa 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 abscissas 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 $V_{½} = u_{½}$

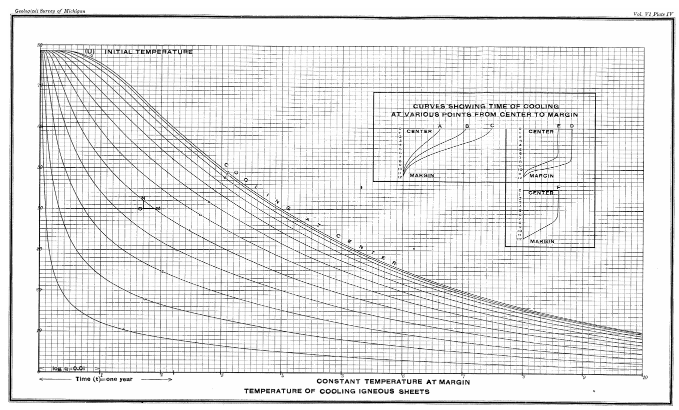


Plate IV. Illustrates the cooling and consequent variation in grain in a sheet which has a uniform initial temperature, the conductivity being as everywhere else in this report assumed as constant. The main plate shows the contours of the surface defining the connection between the time (t), the temperature (U), and the position in a cooling sheet, the interval from the margin to the center being divided into twelve equal parts, and the curve showing the temperature as the time elapses. It is the graphic solution of eq. 11, just as on page 122 gives the numercal solution. The horizontal scale from left to right represents the lapse of time; the distance indicated as equivalent to one year is for the case of a 100-foot sheet, whose conductivity has Kelvin's value. Other conductivities and sizes of sheet merely vary this unit. The original temperature of the sheet (U_o), is taken as π/r, i. e., 0.7854 above that of the margin. This can also be changed to any scale. The smaller curves in the upper right hand corner show the times required to cool through a given interval at various points e. g.

For the curve marked A the interval is from the initial temperature (U_o) 0.7854 to 0.7800; for the curve marked B, from 0.7854 to 0.7500; for the curve marked C, from 0.7854 to 0.7000.

These curves therefore illustrate the variation of grain when solidification occurs at an early stage of cooling, and should be compared with Fig. 14.

For the curve marked D the interval is from 0.300 to 0.250; for the curve marked E the interval is from 0.400 to 0.300, while the curve F is derived from E by taking the square roots of the times as abscissæ, and is to be compared with Fig. 17. These latter curves illustrate the variation of grain when solidification takes place at a late stage of cooling.

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 $t = \log q/\log e^{-1} . c^2/a^2\pi^2$, 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

Table 5. Numerical solution of equation relating to temperature of cooling igneous sheets.

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 thing's to note first. If we suppose the solidification to begin before the rock comes to rest, those crystals which were formed before the rack 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 swine 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 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 conies 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.

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

§ 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., ½ 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 ¼ 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 ½, the ratio will be ½ : ¼ $(1 + ½)^2$ = 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 comparison 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 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 coaling 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.

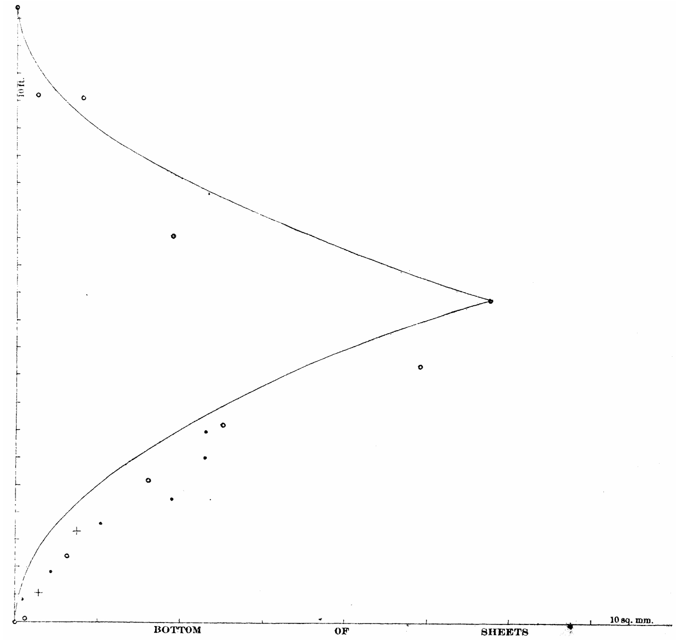


Figure 14. Illustrates the relation of the area of cross-sections of augite crystals to the distance of the crystals from the bottom of the sheet; different signs indicate observations on specimens from different sheets, as follows:
° The Greenstone, Drill hole No. VI, 130-363 ft.; Ss. 15248-58.
• Drill hole No. XIV, 202-367 ft.; Ss. 15804-10.
+ Drill hole No. XVI, 696-786 ft.; Ss. 15934-44.

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 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 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-porphyritic 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.

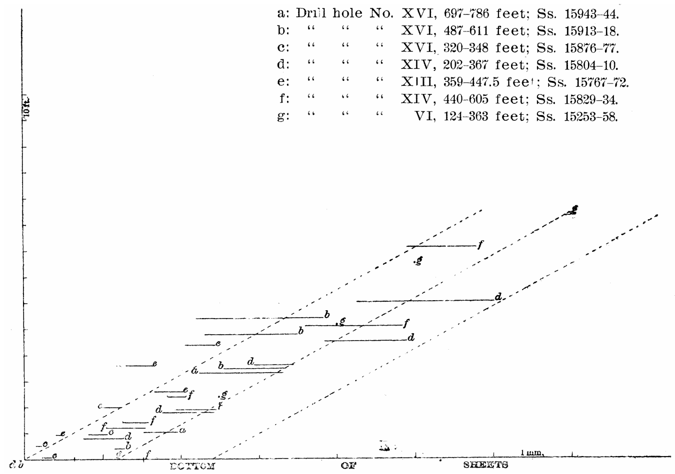


Figure 15. Illustrates the relation of the linear dimensions of augite crystals to the distance of the latter from the bottom of the sheet, in ophites; letters a, b, c, etc., indicate specimens from different sheets.

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 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.

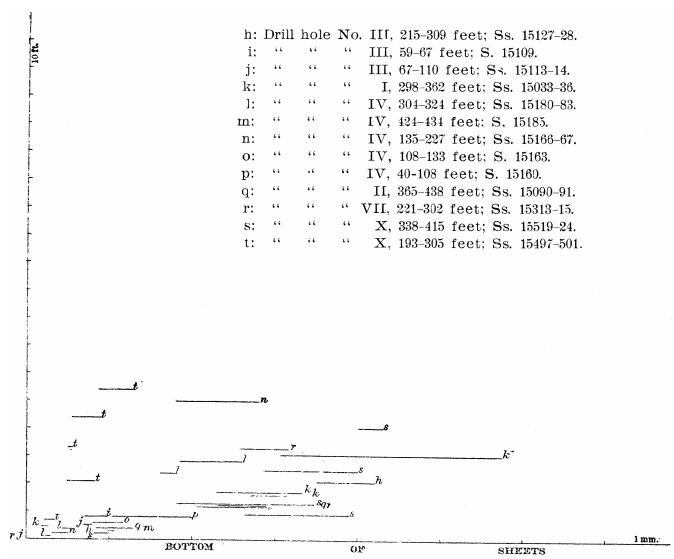


Figure 16. Illustrates the relation of the linear dimensions of augite crystals to the distance of the latter from the bottom of the sheet, in sheets not represented in Fig. 15; letters h to t indicate specimens from different sheets.

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 ($Ab_5\,An_3$) 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.

*These figures represent the actual thickness.

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

(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; 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.

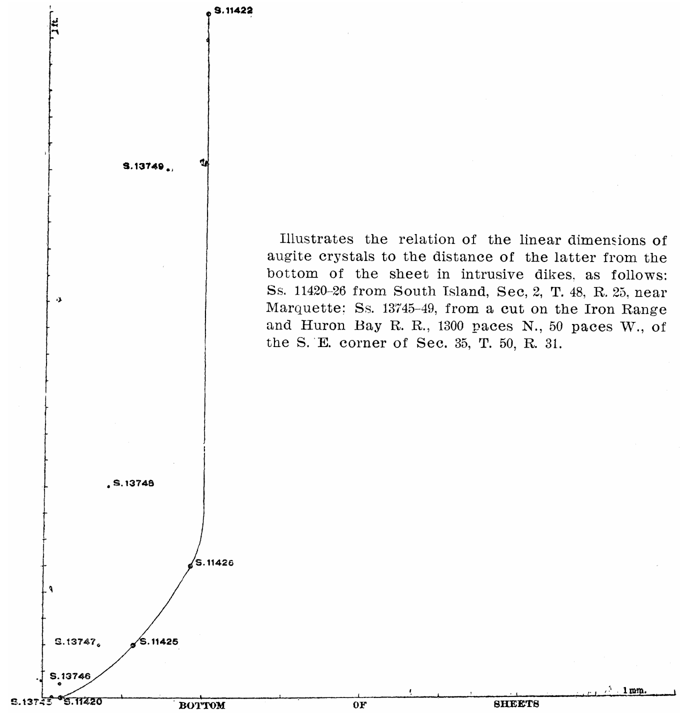


Figure 17. Illustrates the relation of the linear dimensions of augite crystals to the distance of the latter from the bottom of the sheet in intrusive dikes, as follows: Ss. 11420-26 from South Island, Sec, 2, T. 48, R. 25, near Marquette; Ss. 13745-49, from a cut on the Iron Range and Huron Bay R. R., 1300 paces N., 50 paces W., of the S. E. corner of Sec. 35, T. 50, R. 31.

(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 feldspathic—the two in reciprocal relation. These specimens correspond respectively to the dark and light types of diorites (Pumpelly's gabbro) which Marvine 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 differentiation 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 interkneaded 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.

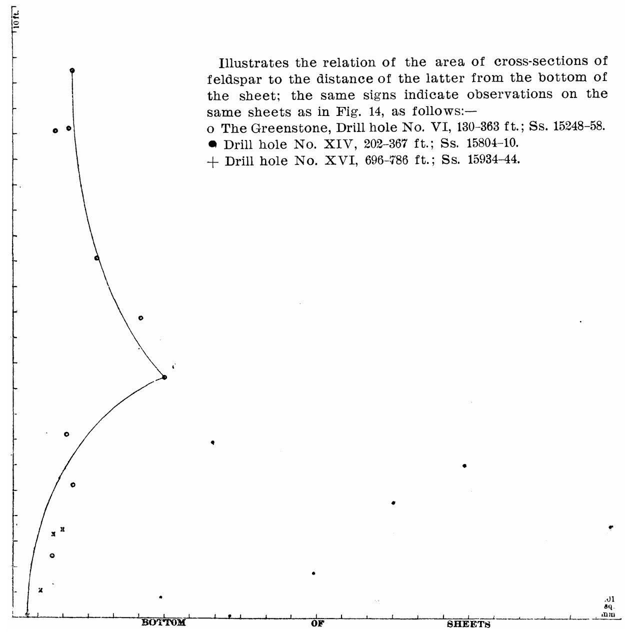


Figure 18. Illustrates the relation of the area of cross-sections of feldspar to the distance of the latter from the bottom of the sheet; the same signs indicate observations on the same sheets as in Fig. 14, as follows:—-
o The Greenstone, Drill hole No. VI, 130-363 ft.; Ss. 15248-58.
* Drill hole No. XIV, 202-367 ft.; Ss. 15804-10.
+ Drill hole No. XVI, 696-786 ft.; Ss. 15934-44.

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. Eight 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 ± = 0.06 x + 1; where x denotes distance from margin; therefore distance from margin is 400 ±, —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 Phœnix 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.

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 les« 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.

*Which we may also write for rough, naked-eye observations, 400 X (size of mottlings in inches) = distance from margin in feet.

§ 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.

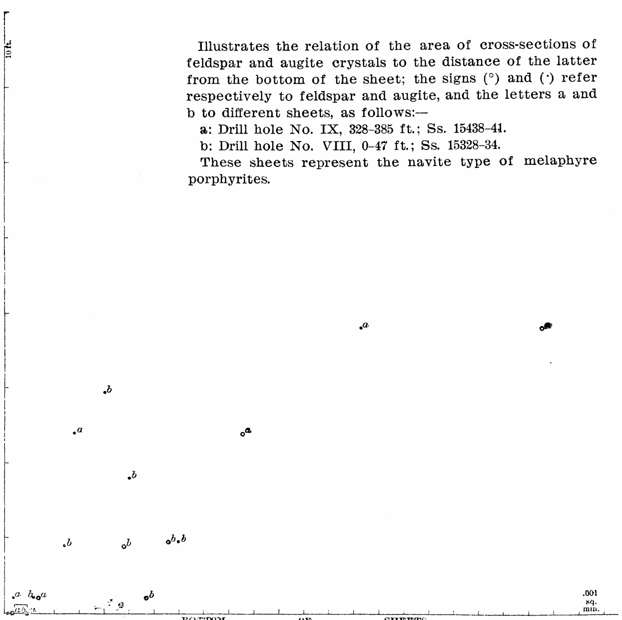


Figure 19. Illustrates the relation of the area of cross-sections of feldspar and augite crystals to the distance of the latter from the bottom of the sheet; the signs (°) and (•) refer respectively to feldspar and augite, and the letters a and b to different sheets, as follows:—

a: Drill hole No. IX, 328-385 ft.; Ss. 15438-41.

b: Drill hole No. VIII, 0-47 ft.; Ss. 15328-34.

These sheets represent the navite type of melaphyre porphyrites.

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 porphyrlte 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 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, I here 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.

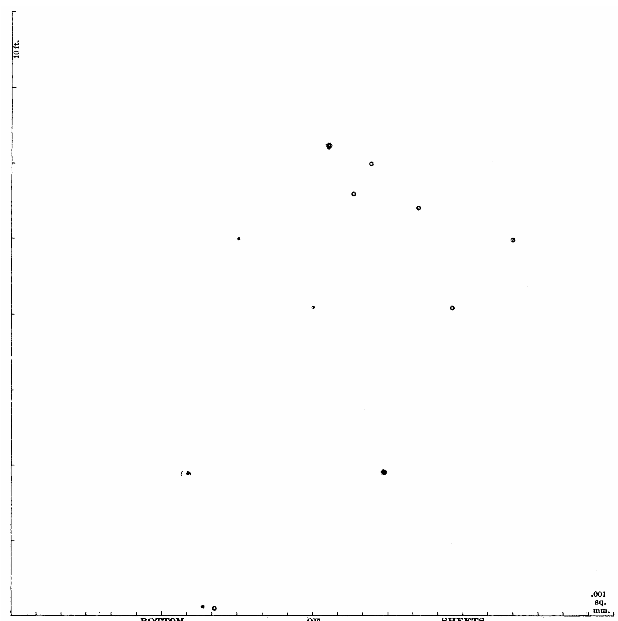


Figure 20. Illustrates the relation of the area of cross-sections of feldspar and augite crystals to the distance of the latter from the bottom of the sheet, in the Huginnin porphyrite, Drill hole No. XIV, 367-436 ft.; Ss. 15811-19; the signs (°) and (•) refer respectively to the feldspar and augite.

(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 other- wise 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:

(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.

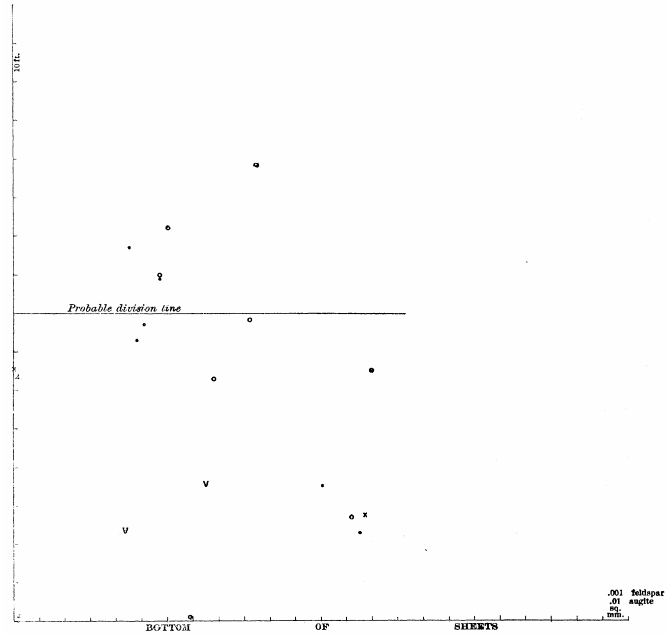


Figure 21. Illustrates the relation of the area of cross-sections of feldspar and augite crystals to the distance of the latter from the bottom of the sheet, in the Minong trap and porphyrite; different signs indicate the various observations, as follows—
• Feldspar, in Drill hole No. I, 426-536 ft.; 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.

§ 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 below. 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 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.

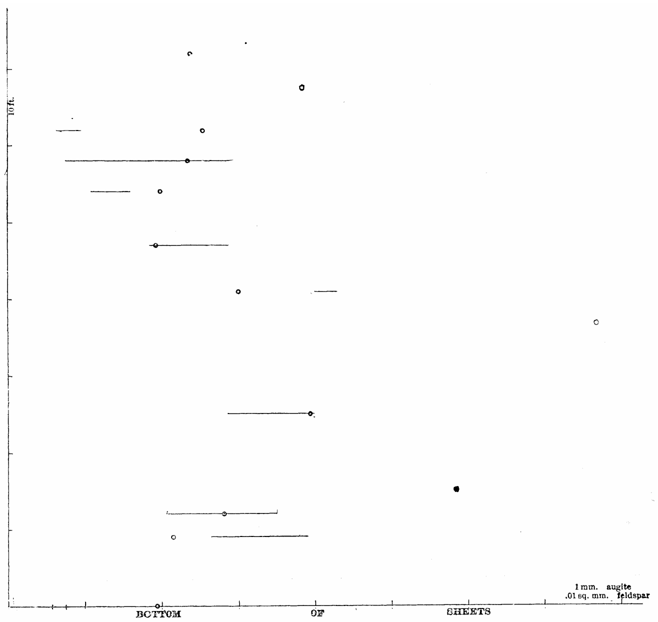


Figure 22. Illustrates the relation of the area of cross-sections of feldspar (o) and augite-crystals to the distance of the latter from the bottom of the sheet, in the sheet that has been analyzed:—
S. 15523 at 9 ft, S. 15519 at 41 ft. and S. 15515 at 62 ft, respectively, from the bottom of Drill hole No. X, 338-415 ft.; Ss. 15513-24.

DR. L. L. HUBBARD, *MARCH 2, 1896.
State Geologist, Houghton, Michigan.

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_2O_3	16.60	18.39	19.79
Fe_2O_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_2O	1.02	1.04	0.52
Na_2O	4.05	3.76	2.55
CO_2	0.40	1.00	0.29
H_2O	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.

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 must not then be applied indiscriminately, but only to the Greenstone and to flows strictly comparable. As we have seen, it does apply fairly well to a large number of other flows among the Keweenaw beds and may thus be considered as characteristic of a standard type, so that variation from it points to abnormal chemical composition. Numerous instances of the smaller grain of the augite have been noted, from actual measurement, in the beds above the Greenstone.

§ 11. Other factors affecting grain.

We have mentioned that there are other factors affecting grain, just as there are other factors affecting the rate of solidification. But our investigations throw little light on them. We have no right to presume any great variation in pressure in the series which we have been studying. The sole exception which we have already mentioned, is that around certain amygdules the grain seems to be finer (Pl. VI, Ss. 15811 and 15008-15117). This can hardly be due to cooling, as the escape of heat into a small closed space like the bubble in which an amygdule is formed, can hardly be more rapid than elsewhere, but this finer grain may easily be supposed to be due to the escape of the gas that caused the bubble. Thus, too, we have around an amygdule in S. 15618, a zone with a trichitic texture of arborescent feldspar. Since, as we have already mentioned, the diffusion of gas follows in general the same laws as the diffusion of heat, and indeed is dependent upon it, our best chance of studying the varying effects of gas diffusion, would be if we could compare some flows which we knew were poured forth under a considerable depth of water, with those which we knew were subaerial. Even then we should probably find that the varying conductivity respectively of water and air was a more important factor. We have not this certainty concerning any of the flows here considered. It has occurred to me that the upper part of the series where sedimentaries are more abundant, and especially the beds around Chippewa Harbor, where the sedimentaries are fine grained sandstones, and seem to be penetrated by intrusive sills, were likely to have been deeper submarine eruptions. It would seem likely that in such a case a flow would be especially liable to be split while hot by a later flow, but that question must await farther investigation.

In the table on the preceding page the CO_2 and H_2O are neglected as secondary additions. The excess of bases in Sp. 15515, 1.15 per cent FeO not accounted for, points to a probable removal of part of the SiO_2 which has been replaced by the CO_2 and H_2O. It would be mathematically easy enough but not physically probable to assume that the iron was added to the augite so as to make a kalk-olivine. Or it is likely that somewhat too much An has been taken, as the determination, by the extinction angles, of ratio of Ab : An may easily be 10 per cent out. Finally, it is obvious by comparison with analysis of No. 15523, that the relative proportion of Fe_2O_3 : FeO is liable to variation which may be due to the character of the secondary alteration. Molecule (3) was very likely in the original glass with SiO_2, now removed. The FeO and MgO are interchangeable in (4) and (7), making a possible variation in percentage there. Query: Is the higher percentage of iron in the olivine in No. 15515 probable, or is it more likely that the iron was present as iron oxide and that the corresponding SiO_2 was used to make orthoclase?

§ 12. Distinction between intrusive and effusive rocks.

The most important bearing of this discussion from a theoretical point of view is on the question as to the recognition of the abyssal or plutonic rocks as a separate group. It has often been denied that we can make any distinction between the more massive basic effusives and the deep seated intrusive, that is, plutonic or abyssal forms of the same chemical composition, while the marked difference between the equivalent more siliceous forms, the granites and rhyolites, is undeniable and generally accepted. But now in view of what we have seen, the question opens whether we may not seek characteristic differences, not merely in the appearance of diallage or augite, which is rather a phenomenon connected with metamorphism and of dynamic origin, but also in the character of the variation in grain. A rock may be looked on with equal justification as a geological unit, or as a mineralogical combination of certain minerals in a certain manner of texture, and according as we look at it our classification will differ, both classifications being equally justified, both having their place. But if we are to consider a rock as a geological unit, as a constituent of the earth's crust, then I presume no one will doubt that we must consider one single sheet of lava or igneous magma as one unit, and then we come to this characteristic difference between the effusives (in general) and the intrusives (in general),—that the former increase in size of grain from the margin clear to the middle, and the others have a more or less broad contact zone of uniform grain, while the deeper seated intrusives, either because of the higher initial temperature of the molten rock itself or because of the higher temperature of the rock into which it was injected, would have no marginal zone of finer grain. Of course, here, as everywhere in nature, we have transitions. It is easy to conceive that flows near their source may be superheated when coming to rest, and to imagine intrusive sheets whose conditions of cooling will approximate to those of effusion. The real determining factors of a rock are not its geological surroundings, but the physical conditions consequent upon those surroundings. These physical conditions will, however, as a matter of fact be closely linked with certain geological surroundings, and whichever we use for our classification, the important thing is that we should be able to read from the present state of a rock the physical conditions of its formation, and hence the probable geological conditions that surrounded it at that time.

Molecules (1).	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	K_2O	Na_2O	CO_2	H_2O	Corresponding percentage.
Equivalent weight (2)	60	102	160	72	40	56	94	62	44	18	
Per cent in analysis of 15515 (3)	46.45	16.60	2.72	7.25	9.21	6.32	1.02	4.05	0.40	5.01	99.03
(3) ÷ 2	0.774	0.163	0.017	0.101	0.230	0.113	0.011	0.065	0.009	0.278	
Feldspar											4.03
Ab — Na_2O, Al_2O_3, 6 SiO_2, using all Na_2O	0.390	0.065						0.065			6.62 23.4
	0.384	0.098									34.06% Ab
An — 2 CaO, 2 Al_2O_3, 4 SiO_2	0.130	0.065				0.065					3.64 6.62
Enough for Ab_2An_3, chap. VI. § 2.											7.8 52.13% Ab_2 An_3.
	0.254	0.033				0.048					18.07% An
K_2O, Al_2O_3, 2 SiO_2; may combine with Ol. molecule for biotite or with 4 SiO_2 for feldspar	0.022	0.011					0.011				1.03 1.12 1.32 3.47% requiring 2.6% SiO_2 to make orthoclase or any amount of olivine for biotite.
	0.232	0.022									1.58 2.24 1.32
*FeO, Al_2O_3, SiO_2, using the remainder of Al_2O_3	0.022	0.022		0.022							5.14%
	0.210	0.000		0.079							1.22 2.72
FeO, Fe_2O_3			0.017	0.017							3.94% Magnetite
				0.062							2.668 1.92 5.76 15.49% augite.
CaO, MgO, 2 SiO_2; augite, diopside, using all Ca	0.096				0.048	0.048					10.35%
	0.114				0.182						7.28 5.46
Balance so far as may be is 2 MgO, SiO_2	0.091				0.182						12.74%
	0.023										
Respectively 2 FeO, SiO_2	0.023										3.32 1.38 17.44% Olivine.
				0.046							4.70%
Excess of bases				0.016							1.15% FeO not accounted for.

* Augite-fassaite molecule.

Molecules (1)	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	K_2O	Na_2O	CO_2	H_2O	Sum.	Sp. Wt.	Corresponding percentage.
Equivalent weight (2)	60	102	160	72	40	56	94	62	44	18			
Per cent in analysis of S. 15523	46.13	19.79	7.24	3.79	7.27	11.43	0.52	2.55	0.29	1.83	100.84	2 887	
(3) ÷ (2)	0.769	0.194	0.045	0.053	0.182	0.204	0.006	0.041	0.007	0.102			
Ab = Na_2O, Al_2O_3, 6 SiO_2, using all Na_2O	0.246	0.041						0.041					2.54 4.18 14.76
	0.523	0.153											21.48 % Ab
An = 2 CaO, 2 Al_2O_3, 4 SiO_2, enough for Ab_2 An_3, chap. VI, § 2	0.246	0.123				0.123							6.89 12.54 14.76 55.67 % feldspar Ab_2 An_3
	0.277	0.030				0.081							34.19 % An
K_2O, Al_2O_3, 2 SiO_2; may combine with 4 SiO_2 for feldspar or with olivine molecule for biotite	0.012	0.006					0.006						0.55 — 0.03 0.61 0.72
	0.265	0.024											1.87 %. Query: In orthoclase or biotite molecule?
FeO, Al_2O_3, SiO_2; the augite fassaite molecule, using the remaining Al_2O_3	0.024	0.024		0.024									1.73 2.45 1.44
	0.241			0.027									5.62 %
CaO, MgO, 2 SiO_2; the augite diopside molecule, using all remaining CaO	0.162				0.081	0.081							4.54 3.24 9.72
	0.079				0.101								19.50 %
FeO, Fe_2O_3; magnetite, using all remaining FeO			0.029	0.029									2.08 4.64
			0.016										6.72 % magnetite.
MgO, Fe_2O_3, SiO_2; augite molecules, using all remaining Fe_2O_3	0.016		0.016		0.016								0.64 2.56 0.96
	0.063				0.085								4.16 % 27.28 % augite.
2 MgO, SiO_2; olivine molecule, using remaining MgO	0.043												3.44 2.58
SiO_2 excess; in feldspar, or in converting olivine to augite	0.020				0.085								6.02 % olivine. 1 20 SiO_2 not accounted for.

With all allowances for interchange of bases and secondary alteration, the relative constancy in quantity by variability in chemical character of the feldspar, the increase in the augite and diminution of olivine as compared with 15515 are clearly indicated. See note. p. 148.

Table 6. Division into molecules of analyses of Ss. 15515, 15523.

The practical question for Isle Royale is whether dikes (or intrusive sheets) do play the important role that they are imagined to by N. H. Winchell (Am. Geologist, 1805, p. 270). There is no doubt that at certain points on the north side of the island the Minong trap does resemble a dike, and in a reconnoissance such as Winchell made might readily be taken for such, and I do not wish to be understood as criticizing Prof. Winchell farther than to say that in a cursory glance at a region out of his particular realm of study he seems to have been mistaken. There are other arguments enough for the non-intrusive character of the Minong trap, but the argument on which we are now dwelling is one that applies equally to practically all the other basic sheets. Their grain increases clear up to the center. Now if we compare Lawson's studies of the intrusive sills and dikes of the opposite or "North Shore," which in all probability represent deeper seated forms of the same general magma, at any rate are very similar chemically (Bull. Minn. Geol. Survey, VIII, pp. 32, 36; Am. Geol., VII, 1891, p, 153 *et seq*.), we find it distinctly stated that there is a *rapid variation in grain for the first few feet from the contact, and then a central coarser belt of tolerably uniform grain*. In the Stop Island dike, for example, he has given the measurements and also distinctly stated that while the dike is 150 feet wide, the grain increases rapidly for the first four feet, then slowly to 15 feet, then there is hardly any perceptible change to the center. The pyroxene, according to his figures, actually diminishes in size (owing perhaps to the chemical differentiation which is the principal subject of his paper). It is easy to see that his statement and figures point to a curve of grain like those of Fig. 17, which are from similar dikes in the South Shore Huronian. It is then evident that the conditions of grain alone would suffice to indicate that the basic rocks of Isle Royale are superficial, and I venture to prophesy that it will prove widely true that *superficial basic rocks are characterized by an increase of grain to near the center, white deep seated basic rocks have a broad central zone of nearly uniform grain.*

It may also be noticed in this connection that Lawson finds the intrusive quartz porphyrites accompanying the basic sills to be granophyric, a form of structure closely akin to the ophitic, but which we have found on the island only in pebbles in conglomerates. It is not impossible that we have here the indication of a corresponding scale of textures for the acid rocks which we have failed to find on Isle Royale, where acid rocks are the exception (Cf. Ros. M. u. Pet. Mitth., XII, 1891, p. 379).

The bearing of the above remarks upon the controverted question of the effect and importance of the geological environment ("Ort") upon rocks is too obvious to need explanation. The only thing to be noticed is that it introduces a factor hitherto disregarded, the temperature at the end of motion, as an important one. It must also be remembered that the possession and loss of gas by diffusion follow the same laws as the possession and loss of the imponderable "caloric," while the possession of gas may greatly lower the temperature of solidification as glass.