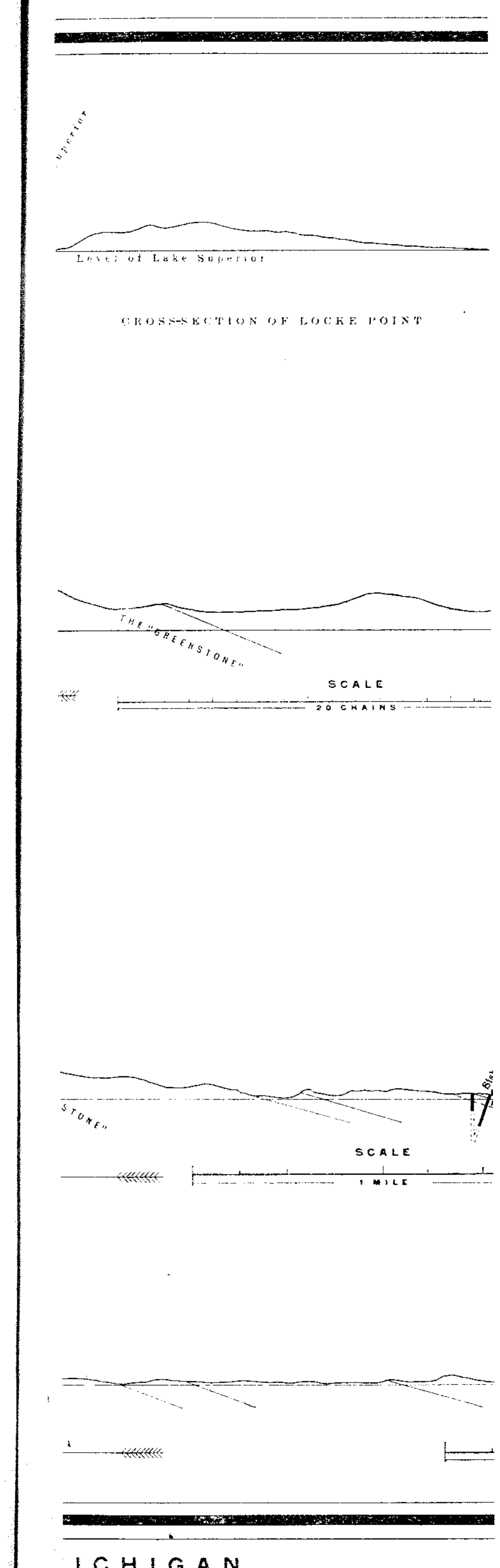
their general character. In general the heave in any one does not appear to be above a few feet, though the aggregate may be considerable. The faults seem in general to be nearly parallel to the well marked, nearly vertical joints. These are quite conspicuous in the Cumberland Point conglomerate and run N. 5° E., magnetic. The question arises in connection with the nearness of the Cumberland Point conglomerate to the Greenstone range whether this proximity is due to the thinning of the intermediate trap beds, or to the dropping out of the uppermost of them, so that the Cumberland Point conglomerate may represent also some of the conglomerates cut in drill hole No. XI, or whether we have an unconformable overlap of a more recent formation, the thinning being due to greater erosion. Now there are some reasons for believing that all three of these explanations are partially true. The conglomerate contains numerous trap and amygdaloid pebbles, and even occasional agates such as occur in the traps. But dismissing the question until we take up the south half of the island, we see that it will be safer to estimate the general thinning of the formation from lower horizons, rather than from the assumption that the Cumberland Point conglomerate represents the same horizon as the conglomerate on the shore of Siskowit Bay.

Leaving the west end of the island and sailing along the northwest coast, we see that we are following very nearly the strike. The large ophite which comes just above the Huginnin porphyrite may be seen rising and falling, sometimes at the crest of the ridge and leaving room for some smaller amygdaloidal beds beneath it,—the thompsonite amygdules of which are abundantly collected on the beaches,—and again coming down to the water's edge. Small gaps in the coast seem to indicate faults, and at Todd Cove this front range is broken through. At Todd Harbor it forms Wilson Point, the outer protecting point of the Harbor being a very coarse ophite, the augite patches being 2-3 cm. in diameter. On certain parts of this point, e. g., Sp. 16022, 1480 paces N., 650 paces W., in Sec. 10, T. 65, R. 36, there are good illustrations of the coarser feldspathic and porphyritic streaks which are a feature of these coarsely lustre mottled ophites, or gabbros as they would be called by many. Most of the exposures around the harbor are of ophite, but the point between Florence and Pickett bays at 1150 paces N., 10 paces W., shows a contact at its northeast end with some sediment and a well defined dip of about 32° to the southeast (Fig. 26).

The attitude of the various joints also indicates about this dip. The exploratory work of the Isle Royale Land Corporation we have already described. Continuing southeast from the costeans, along a trail which runs diagonally across Sec. 13, T. 65, R. 36, we pass over a comparatively flat highland, with occasional benches, and outcrops of ophite whose occurrence and the coarseness of whose grain we have taken into account in locating the Greenstone on our map. It is not until we have reached the east section line of Sec. 24, in the same township, where the trail turns and runs south, that about 1580 steps N. of the S. E. corner we find a coarse diabase porphyrite with occasional large porphyritic crystals, a bed which appears to be above the Greenstone, and to correspond with that which passes through Double Island and Washington Island. Continuing south, the last outcrops, which are most extensive and characteristic, are from 530 steps to 430 steps north of the corner, and are typical porphyrites of the Ashbed type, with occasional round green balls, with amygdules often large and irregular, with shells of quartz, some white radiated mineral (prehnite?) and datolite (Sp. 16002-16005). The partly empty cavities show at times copper crystals. Continuing along the coast from Todd Harbor we see gaps in the ranges running nearly north but a little east and probably indicating faults. On Hawk Island we get a bed of sandstone representing one of the conglomerates of drill hole No. XII in our geological column, which gives a reliable dip of 26° toward S. 32° E. Neither the bed above nor that below the sandstone is distinctly mottled. The lower one contains some amethyst. The sandstone is dark chocolate colored and there are boulders of conglomerate on the island. Below the sandstone is a bed of trap more than 50 feet thick containing some amethyst and above it another more than 30 feet thick.

Coming to McCargoe Cove we encounter the largest break on the island. Artificial exposures of the Minong trap on the west side and natural ones on the east side give a good opportunity to estimate its displacement, and all the ridges clear through to the south side of the island appear to be shifted. Immediately to the west of the entrance of the cove the Huginnin porphyrite is well exposed, showing that we have on the whole followed along its strike, and preparing us to meet the Minong trap, which is here found to be at a proper distance from it. (See cross-section G-H, Pl. XIII.). I have already described the Minong mine. On the east side of the cove I was able to find no trace



of the Minong porphyrite, though exposures are numerous,—another indication of the fault. Though the Huginnin porphyrite is not exposed on the east side of the cove, judging from the big mottled ophites which overlie and underlie it on the west side and are assumed to correspond with similar beds seen on the east side of the cove (which, however, is rather an unsafe deduction, as there are a number of similar beds at this part of the series), the east side is thrown north, as appears also to be the case with the Minong trap, but farther south the throw seems to be the other way. Amygdaloid Channe' may represent one of the lower conglomerates, but no sign of the bottom felsite has been seen here. The dip, however, is high as indicated by the jointing of the traps, and also by a thin bed of sandstone on Amygdaloid Island. The south side of Amygdaloid Channel has a very well marked terrace, and most of the exposures are of mottled melaphyres, ophites.

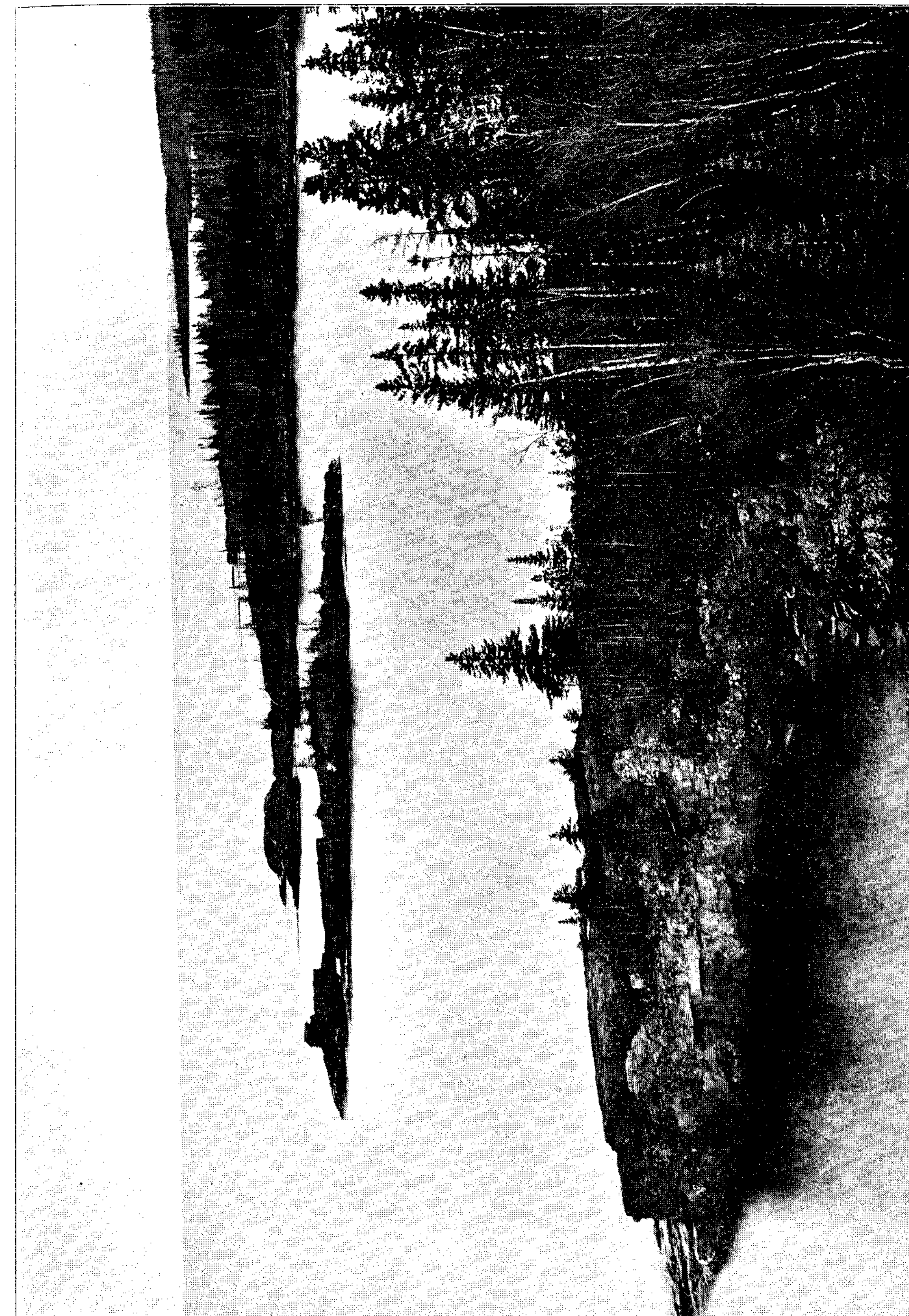
Coasting on, the Minong trap is again found, as indicated on the map and cross-section A-B, Pl. XIII, and in Blake Point we meet again the Greenstone, which has been tracked by a series of cross-sections, and proved continuous from the other end of the island.

Sections over Blake's Point show that it is skirted by the porphyrites on its south flank, as indicated on the map and cross-section C-D, Pl. XIII. Near the west quarter post of Sec. 13, T. 66, R 34, we find a valley, and exposures of conglomerate which we take to be equivalent in horizon to the red sandstone in drill hole No. VIII, 337 (=1524 feet of the column)

§ 4. Southern rock exposures.

On the south side of Rock Harbor we find outcropping on the island sandstone and conglomerates, which indicate that we are near the top of the Lower Keweenawan, and as the maps show, the south side of the head of Rock Harbor is lined with an alternation of sandstones and traps which appear to be tolerably continuous bands, and though, in view of the number and exact resemblance of the sediments on the one hand and the traps on the other and the gentle but variable dips, and variations in altitude, I can hardly hope to have connected all the isolated outcrops exactly, yet many of them have been quite continuously traced and the general arrangement cannot be far wrong. It is very noteworthy that while on the north side of the harbor the ridges show no sign of disturbance, near the head of the harbor on the south side the dips are very flat, at times not over 4°, and the strike, while of course difficult to determine with precision with such flat dips, veers around from southwest to south. This is not due to a mere flattening of the dip toward the center of the Lake Superior basin, for when we come to Chippewa Harbor we find the dips as steep as ever (cross-section G-H, Pl. XIII), but the strata appear as though wrapped over some large mass below. This suggests either that there is an intrusion below or that we are on the flanks of an old volcanic focus. As confirming these suggestions, we find on following the shore, that the traps dip lakeward all around the protrusion of the coast from Conglomerate Bay to Chippewa Harbor (Plate XIV), and that parallel to the dip are numerous apparently intrusive sills. These are a very curious feature, as they run almost as regularly as beds and are extensive and thin. Near the Saginaw Mine there are four such thin belts. Sometimes they are only an inch or two thick and I gather from them and from certain seams of indurated red clay, which near the trap is epidotic, the impression that the igneous action was submarine, and that it was as easy for the lava to intrude itself into the mud or to split up a previous sheet, as it was to flow out directly beneath the sea. Moreover the associated sandstones are very often fine grained and not conglomeratic.

At the entrance to Chippewa Harbor and back of the neck where the fishing station is, there is well marked faulting, and from there on to the middle of Siskowit Lake there is more evidence of faulting of considerable throw, than elsewhere on the island. The throw at Chippewa Harbor is given by Foster and Whitney as 971 feet "in a linear direction" (i. e. horizontally?). The little cove on section 19, T. 65, R. 34, about two miles southwest of the harbor, shows also a throw, and near the mouth of Siskowit Lake the conglomerate is apparently thrown—by the McCargoe fault—directly in the way of the amygdaloids. The exact contact is not exposed, as there is an interval of about 300 feet between the nearest outcrops. Comparing the exposures around Siskowit Lake with those around Rock Harbor, it is evident that, toward the southwest the traps are running out. For on the south side of the west end of Siskowit Lake there is a ridge of conglomerate much thicker than any around Rock Harbor that is equally coarse, and the breadth of traps above the range of melaphyre porphyrite is obviously much less. It would therefore be quite natural to suppose that the irregular rela-



VIEW FROM ROCK HARBOR LIGHTHOUSE, LOOKING SOUTH.

tion between the conglomerate and volcanic series on the north side of Siskowit Bay is due to the disappearance of the traps or to an erosion unconformity, and the fact that the conglomerate is made up of pebbles of basic as well as of acid volcanics, plagioclase porphyrites, amygdaloids, diabases, etc., red carnelians, agates, and other secondary quartz pebbles, would strengthen the latter conclusion. But on the other hand the fact that the abnormal contact comes immediately in a line of disturbance, and the further fact that the supposition of an unconformity would involve an almost overhanging cliff, are arguments in favor of a fault contact, and the traps seem too thick south of the head of Siskowit Lake to disappear so suddenly. The shore of Isle Royale for the rest of the way westward is conglomerate and sandstone, and Point Houghton is made up of a great series of sandstones dipping at a considerable angle,—from 15° to 22°,—whereas along the north side of Siskowit Bay the dips are flatter. All around the bay there is a very prominent jointing nearly perpendicular, but inclining a little so as to dip to northwest and striking between N. N. E. and N. E. This jointing is thus very nearly parallel to the direction of the fault we have supposed. Another interesting feature is found on Hay Point in the shape of a large calcite vein striking N. 63° E., and dipping 25° to S. E. In other words its strike is very nearly that of the formation, but the dip is somewhat steeper. This is very much like the calcite vein also mentioned by Jackson and Foster and Whitney, near the entrance to Rock Harbor (F. & W., *loc. cit.*, p. 82) and indicates a kind of motion which is very difficult to detect, i. e., faulting along planes near the bedding. Turning now a back glance upon the region around Chippewa Harbor, we see that

(1) In increasing thickness of individual beds,

(2) In longer duration of the igneous action as indicated by unusual development of the upper part of the series,

(3) In greater disturbance by faults,

(4) In the presence of sheets apparently intrusive (and I may mention here that about 60 steps north of the southeast corner of Sec. 27, T. 66, R. 35, there is a small intrusive dike following various joints), there are indications that we are here at the nearest point on the island to an old focus of eruption.

CHAPTER IX.

CHEMICAL PROBLEMS.

§ 1. General chemical character of the series.

The chemical interest of the rocks of Isle Royale gathers mainly, in the first place, around the variation in the character of the melaphyres, and secondly around the processes of concentration by which the copper has been formed.

The red distinctly felsitic rocks are, as we have said, comparatively rare, except as pebbles in the conglomerates. Investigations into their chemical character may therefore be more profitably postponed until we can consider them in their original beds, e. g., in connection with the felsites of Keweenaw Point. There are, however, at least two beds on Isle Royale, beside the felsite at the extreme bottom of the series (whose outcrop would be at the bottom of the lake), which belong to the felsitic series, namely the upper Minong bed which is at times a porphyry of the orthophyre series, at other times more of a felsite porphyrite or oligophyre,—the other, the Huginnin porphyrite with much more pronounced and conspicuous porphyritic oligoclase crystals or phenocrysts. Leaving these and a few doubtful beds out of account, the rest of the series is composed wholly of beds whose essential mineral composition is similar. They have a plagioclase, some augite, altered olivine, and in some shape the iron ores. They are thus all entitled to be classed as melaphyres.

§ 2. Variation in the chemical character of the melaphyres.

There is a wide divergence in character among these melaphyres, a difference obvious not merely microscopically but to the naked eye, corresponding to the difference between the melaphyre ophites and the melaphyre porphyrites which we have already described. As we have said, the melaphyre porphyrites are lighter colored, incline to have a smoother, more conchoidal fracture and to be more pronouncedly porphyritic, through clusters of feldspar crystals. When they are coarse

grained they are much more conspicuously feldspathic, the augite being hardly recognizable. The amygdaloidal pores are liable to be but partly filled and then often with analcite or quartz, while in the ophite they are generally completely filled with calcite, prehnite, laumonite, etc. Under the microscope, in the porphyrites the augite appears much less in quantity than in the ophites, and very often idiomorphic, the feldspar is oligoclase more often than labradorite, but the olivine is more conspicuous.

Now let us seek what chemical fact these differences express. Analyses I–IV are from the most typical bed of the Ashbed diabase porphyrite type, while V, VI, VII, are from a bed of intermediate character that occurs immediately above the former, and below the first scoriaceous conglomerate, which corresponds to Marvine's bed No. 44. Comparing these with other analyses of some of the more ophitic of the Keweenawan rocks (VIII–XIV), including one of the Greenstone, we see that the variation in the two types is not dependent on a great change in the percentage of silica. But I have already called attention to the fact that there is a greater abundance of augite in the lower part of the upper bed which manifests itself also in the size of the grain (p. 146).

There is, as we can see, a slight but uniform and perceptible increase in the amount of silica accompanying this differentiation and disappearance of augite, but obviously this is not the distinguishing feature and it is a stretch of language to speak of the one type as more basic than the other, in spite of the fact that macroscopically the augitic type looks very much more like what we are wont to call basic. The essential factor is the variation in the amount of lime (CaO) and soda (Na_2O). We know that the olivine crystallized out at a very early stage, while the magma was still quite hot and in motion, but the differentiation does not seem to be due to any settling of the olivine to the bottom. In fact the olivine is more conspicuous, and the magnesia (MgO) quite as abundant in the upper part of the flow. The olivine seems rather to have been more strongly attacked at a later stage, the more calcareous the residual magma was.

On the other hand, the presence of porphyritic feldspar clotted together (glomero-porphyritic) and consisting of oligoclase, is characteristic of these rocks, and such differentiation as we find indicated by Ss. 15515–15523 may be explained by supposing that we had originally a magma containing so much soda (Na_2O) that oligoclase, which is less fusible than labradorite, and therefore could form at a higher temperature, was early formed and rose to the top until the percentage of soda was so reduced as to form a more stable mixture, in which the lime and soda were in such proportions as to make labradorite, and the lime so abundant as to make augite the last silicate to form, while in the upper zone the sodiferous character of the rock was accentuated. This we may suppose all took place, to some extent at least, before the magma came to rest, in the earlier stages of cooling and at the higher temperatures. Then in the latter stages of cooling and at a lower temperature the olivine would be attacked by the calcareous magma to form augite.

Now the group of melaphye porphyrites—the Ashbed type—form one of the best marked horizons in our series and occur not merely in one bed, but in many beds of somewhat varying habit, and of more or less pronounced character, so that it seems probable that we should not look to any surface conditions, but to deep seated magmatic changes for their origin. It may well be that the change which produced the group took place while the magma was yet in the earth, even though in such cases as Ss. 15515 to 15523 the differentiation has continued even in the individual flow (See pp. 145-151).

One other question suggests itself. May the peculiar character of the relations of ophites and porphyrites be due to the intermixture of the two magmas? To this we can reply that the change from melaphyre porphyrite to the ophites involves no marked increase in potash (K_2O), nor in silica (SiO_2), as would be expected if the character of the former were due to admixture of a felsitic magma. Analysis VII, which is an ophitic rock carrying labradorite, has only a shade less silica than analyses III and IV, where the augite is in small idiomorphic prisms. The alumina (Al_2O_3) is distinctly associated with the soda in variation. The total amount of iron does not vary much and the relative proportions of ferrous and ferric iron appear to be mainly dependent on the state of the weathering, the green chloritic rocks having the more ferrous iron.* The lime and the soda are however very significant. They are inversely related, the more of one, the less of the other, and the more soda there is, the less augite there is. This is perfectly plain in studying the first seven analyses made for me. Now it must be remembered that three of these analyses are of samples from the same flow, and traces of a similar change in character may be seen in numerous other flows.

*Or does the state of the iron determine the character of the weathering?

Number	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.	XIII.	XIV.
Reference No.	15537	15537	15533	15533	15515	15519	15523							
SiO_2	49.27	49.36	47.25	46.99	46.45	46.25	46.13	47.97	49.20	46.32	50.03	49.15	47.25	50.20
Al_2O_3	16.75	16.05	lost	18.47	16.60	18.39	19.79	15.56	16.00	15.95	15.38	21.90	31.56	15.43
Fe_2O_3	7.78	lost	lost	4.44	2.72	7.70	7.24		3.03	0.86	11.78	6.60		
FeO	4.86	4.84	7.19	7.24	7.25	3.52	3.79	12.41	7.10	8.92	3.90	4.54	2.29	13.79
CaO	5.47	5.66	9.61	9.53	6.32	12.19	11.43	7.07	3.44	10.23	5.39	8.22	15.39	5.47
MgO	7.44	7 27	5.94	6.03	9.21	4.65	7 27	8.28	6.98	4.08	3.60	3.03	0.27	8.62
K_2O	0.48	0.49	0.40	0.33	1.02	1.04	0.52		1.31	1.23	1.14	1.61	0.37	
Na_2O	5.42	5.31	3.42	3.37	4.05	3.76	2.55	6.24	5.05	3.56	5.01	3.83	2.52	4.75
H_2O				3.90	5.01	3.41	1.83	2.46	4.51	3.25	2.73	1.92	0.40	1.74
P_2O_5											(0.33)	(0.33)		
TiO_2									2.26	2.78		0.18		
CO_2	(0.92)				0.40	1.00	0.29							
Ignition Loss	3.72	3.81									0.98			
MnO	tr	tr	tr	tr	tr	tr	tr		1.17	0.89				
Sum	101.19			100.30	99.03	101.91	100.84	99.99			99.94	100.80	100.05	100.00
Sp. Wt.	*2.806			*2.901	2.781	†2.866	2.877			2.6–2.73				

There is generally a trace of MnO (included in summation with CaO.).
*Average of three observations each.
†2.874, 2.859, 2.869, 2.863.
I and II are check analyses sampled only six inches from the bottom of the most typical porphyrite of the Ashbed type.
III and IV are check analyses sampled respectively 16 feet and 19 feet from the top of the same bed, which is at the bottom of drill hole X, 426–483.
V, VI, VII } Flow varying from porphyrite, Sp. 15515 to ophite, Sp. 15523, drill hole X, 338-415 { 65 feet from bottom. / 43 feet from bottom. / 9 feet from bottom.
VIII. Fine grained, from shaft at Rock Harbor, 15 rods north of Ransom, (F. & W. II, p. 88.) On p. 87 they give a partial analysis of the wal of Shaw's vein, Isle Royale, 26.95% soluble in H NO_3 58.09% soluble in HCl, including separated SiO_2. Loss on ignition, 2.20.
IX. Eagle River section, Marvine's bed No. 87, middle of bed (Pumpelly, Proc. Am. Acad., xiii: 285; analyses IX and X by R. W. Woodward.)
X. Irving quotes p. 66 (misprint, CuO for CaO). Bottom of same bed as X; Sp. Wt. 2.73–2.75.
XI. Streng's "Melaphyr Porphyr," Irving quotes p. 277.
XII. Streng's (Duluth) hornblende gabbro; Irving quotes p. 270. This rock shows plainly fluidal arrangement of porphyritic feldspar, mainly oligoclase.
XIII. Anorthosite (822); Irving, *loc. cit.*, p. 438.
XIV. Greenstone, (F. & W. II, p. 38), summit of ridge at Cliff Mine, i. e., 100-200 feet above bottom of flow, probably.
Besides these, Jackson reports the analyses of anhydrous prehnite and chlorastrolite. Whitney reports the analyses of pitchstone, pectolite and wollastonite, (F. & W. II, p. 106).

Immediately at the upper and lower contacts the character of the rock cannot be so well made out, but appears to be intermediate. But about a third of the way from the bottom the feldspar appears most basic and the augite most abundant, while at an equal distance down from the top of the flow, feldspar and feldspar phenocrysts continue very abundant and oligoclastic (e. g. Ss. 15490–15501, 15509–15512).

From rocks like Lawson's malignites (Bull. Geol. Dep. U. Cal. I, 12, p. 337) and from the normal felsites, these melaphyre porphyrites are separated by a high proportion of soda to potash, though the per cent of silica is very similar. These melaphyres have also much more iron.

§ 3. Concentration of copper.

The second point of chemistry which I would like to mention, concerns the concentration of copper. The general paragenesis of the copper in the Keweenawan, having been fully considered by a previous Michigan geologist (Pumpelly, Vol. I, Pt. II, Chap. III), need not be repeated here.

A recent paper by H. L. Smyth is however of such interest as to deserve remark here, especially as it might otherwise probably be overlooked. An abstract is as follows:—(Science, Vol. III, No. 59, February 14, 1896.)

Basing his theory upon the paragenetic series worked out by Pumpelly (*loc. cit.*), he calls attention to the fact that the earlier minerals which preceded the copper are mainly chlorite and non-alkaline hydrous silicates. The later minerals "are alkaline, and are close contemporaries of the copper. Among them are apophyllite (a fluorine mineral), and datolite (a boron mineral)." From the conditions of formation of the separate flows and the intercalated conglomerates, each flow after consolidation was immediately subjected to surface weathering and later buried. The earlier non-alkaline minerals were, he conceives, produced by this surface weathering, the alteration progressing from top to bottom in each individual bed.

"Afterwards came the northerly and northwesterly tilting, and the formation and filling of the fissures, and the impregnation and partial replacement of the amygdaloids and conglomerates. The new minerals of this period are sharply separated from the alteration products of the first which they often replace, by their richness in alkalis, and the presence of fluorine and boron. The two periods therefore are far separated

in time as well as by the character of the chemical agents at work, and do not, as Pumpelly supposed, represent a continuous march of alteration."

Prof. Smyth concludes finally that the copper was not derived from overlying sandstones nor from the traps themselves, but from a deep seated source, and that it was transported by ascending solutions, and probably precipitated as Pumpelly had suggested.

Now as bearing on the argument of this paper we may remark that the universal, and with rare exceptions, complete alteration of the olivine, even in these deep drill cores, lends weight to Smyth's theory that part of the alteration was independent of the present surface of the ground. Moreover, as we have seen, for a considerable thickness of the geological column there is no debris that cannot be considered of local origin, so that it is perfectly possible to suppose that the flows from near the bottom of the series to about the time of the Island Mine conglomerate were sub-aerial. The presence of fluorite also is another point which would tend to confirm his theory as to the action of fluoriferous and boriferous solutions in the mineralization of the beds. But on the other hand I confess I cannot believe in the great interval and wide gap that he supposes between the later copper-bearing and earlier silicates. If there is one mineral with which the copper is more particularly associated than with others it is prehnite, which is not boracic, nor does it contain fluorine so far as I know. Datolite is fairly widespread, but by no means a necessary accompanist of the copper, while apophyllite and analcite are rather curiosities than otherwise, and are said to occur on Keweenaw Point more in the upper levels, which is hard to understand, if they are of deep origin. Moreover the copper is undoubtedly more abundant, the more decomposed the rocks are, and the whole microscopic appearance is that the prehnite is as much a decomposition as an impregnation mineral. Moreover, as will be seen on reference to the geological column, the analcite seems to be especially associated with the more sodiferous melaphyre porphyrites of the Ashbed type. The presence of beds of strongly contrasted chemical character seems to favor the accumulation of the copper, and if the copper is of deep seated origin it is hard to understand why we should not see more traces of it close to veins in the basic sandstones of the Upper Keweenawan. Furthermore we find copper associated with the Triassic traps of the Atlantic coast, which are chemically similar, though so different in time and place of origin. I must therefore believe, without denying that deep seated thermal waters may have had a share in the process of concentration, that the copper is in the case of the Keweenaw traps derived by a process of lateral concentration. And, moreover, the fluorine and boron that are present are not more abundant, one would think, than might easily be accounted for by derivation from the original traps and the vapors immediately associated with their eruption. It is noteworthy that boron minerals are more abundant than minerals of fluorine, which corresponds to the fact that basic beds are more abundant than acid, for boric exhalation and minerals have long been known to be associated with eruptions of basic rock, and fluorine exhalations with those of the siliceous rocks.

CHAPTER X.

DIABASES, PROBABLY KEWEENAWAN, INTRUSIVE IN THE HURONIAN.

§ 1. Introduction.

It seems to be proper to single out for presentation now from among my descriptions of the rocks of the iron-bearing series, the publication of which has been delayed by various causes, that group which in all probability is the intrusive equivalent of the rocks whose descriptions make up the bulk of this volume—I mean the pipes and necks leading to the Keweenaw flows. It will be instructive to thus contrast the deeper seated and surface types, just as Iddings has done for the rocks of Sepulchre Mountain and Electric Peak. Since, in comparison with most of the rocks of the Huronian, they are not dynamometamorphosed, cut the formations up to the base of the Eastern sandstone, and are chemically nearly allied with the Keweenawan traps, the latest series of dikes found cutting the rocks of the iron country have always been considered as intrusive equivalents of the Keweenawan.* As such, therefore, they are equivalent to the intrusive "Logan sills" and accompanying dikes described by Lawson† from the north shore of Lake Superior, the latter standing in the same relation to the Isle Royale rocks, that the former do to the rocks of Keweenaw Point.

Inasmuch, therefore, as the general petrographic descriptions, of which these were a part, have been so long delayed in publication, and are not yet in immediate prospect of appearing, while monographs XIX and XXVIII which have been recently issued by the United States Geological Survey make their issue without considerable revision inadvisable, for many descriptions would be superfluous and many references should be inserted, the description of this particular group may well be incorpo-

*Geol. Surv. of Mich., Rominger, V., 1893, p. 6; Seaman in Wadsworth's report of the State Geologist for 1891-1892, p. 139; Bayley and Van Hise, 15th Annual Report, U. S. G. S., pp. 516, 644.

†Lawson, Bull. No. 8, Geol. Survey of Minn. Also American Geologist, vii, 1891, p. 153, Also cf. Wadsworth, Bull. 2, Minn. Survey, and Mon. XIX, U. S. G. S. p. 349.

rated in this volume to give an opportunity for contrasting superficial and deeper-seated forms of basic igneous rocks. There has been great confusion in times past between these kinds of rocks, which still continues. The American Geological Railway Guide speaks of copper being found in a great trap dike on Keweenaw Point, and, as we have seen, N. H. Winchell and I differ as to the presence of trap dikes on the north shore of Isle Royale (p. 150). Again, in the Minnesota Bulletin No. 8, on the Logan sills just mentioned, we find Lawson challenging the statements of various authorities as to the existence of diabase flows in the Animikie.

§ 2. Use of term diabase.

One word as to nomenclature. The use of the words diabase, melaphyre, basalt and gabbro, have been various. For us a diabase is a characteristically intrusive, not too coarse grained, rock of the same chemical composition, and essentially the same mineral composition as a melaphyre. The word "characteristically" is inserted to rule out small dikes intruded so close to the surface as to differ in no textural respect from a melaphyre. The rocks here included have textures which indicate clearly their intrusion. On the other hand the words "not too coarse grained," which I trust may be later replaced by a more exact definition, are intended to rule out the great massive "batholitic" intrusions which have been by common consent called gabbros. Thus my idea of diabase is a rock in small intrusions, in other words belonging under Rosenbusch's group of "Gang-Gesteine." I thus follow the road indicated by Rosenbusch on p. 520 of the second edition of his "Mikroskopische Physiographie," 1887, rather than the path he himself has followed in his third edition (1896, p. 1093) where he includes under diabase both intrusive and effusive types, and ranks the group among the "Erguss-Gesteine." But we have two terms already for the effusive forms of the gabbro magmas. What object is there in adding a third?

If it be granted that there is an independent and characteristic type of small intrusions, I do not fear severe criticism of my terminology. Criticism of my usage will come most forcibly from those who do not believe that the small intrusion can be distinguished from the effusion type, and interpret otherwise what I conceive to be characteristic textures. I presume Rosenbusch would gladly have followed the path

which he indicated, if he had found that facts justified it. That he did not do so makes me doubt my own conclusions, but after all I can but present the case as I see it and leave time to judge the event.

CHARACTERISTICS OF SMALL INTRUSIVES.

The signs of effusion or of intrusion * may be looked for (A) adjacent to the rock, (B) along the contact, or (C) within the rock itself. It is only in case characters of this last type are present that we should be justified in giving different names to effusive and intrusive forms of the same magma.

(A) As regards the adjacent rock, (1) it is baked and new minerals of various kinds are formed, the well known phenomena of the contact zone. If these occur both above and below a sheet we are quite justified in regarding it as intrusive, whereas the sediment on top of effusive sheets shows little or no sign of contact action, though induration may be merely secondary and occur above a flow. (2) On the other hand the sediment above an effusive sheet (and below as well) may be partially composed of fragments of the latter, i. e., tufaceous. This is a sign of effusion. Friction breccias may occur above and below an intrusion and the overlying rocks may be fractured and disturbed as well as the underlying. An intrusive may enclose fragments of underlying rocks as well as overlying rocks and, generally speaking, its action upon them is more energetic.

(B) As to the contact:

(1) An intrusive rock is liable to send out fine strings and fingers, both above and below, into the strata between which it lies, and though it may follow the lines of sedimentation more or less, it is very likely to jump across from one set of bedding planes or cleavage planes to another.

(2) A flow is theoretically accordant with the bedding planes below if poured out beneath the sea. In the same way if not conformable with the beds above, the unconformity is an ordinary erosion unconformity, not one of intrusion, and the difference is often recognizable, in a number of slight marks for which no short general statement can be given. The characteristic clinkery "aa" surface or ropy "pahoehoe" surface of a flow is often recognizable.

*Cf. Mus. Comp. Zool. Bull. XVI, 6, pp. 100-102.

(3) Sandstone veins or clasolites of fine mud, ramifying into the igneous rock, in wavy or contorted, or sometimes horizontal lines of stratification, are also a feature of effusives. They probably often fill shrinkage cracks.

(4) The flow lines and crystals formed before or during the flow are wrapped around the irregularities of the surface of igneous contact, i. e., the lower surface in flows, both surfaces in intrusive sheets.

(C) Among the characters of the rock itself we may mention:

(1) The generally more symmetrical character in a sheet or dike, especially as regards the jointing, which will be approximately the same for the two surfaces. This is not true in a flow. (Cf. J. P. Iddings, Am. J. S., 1886, xxxi, p. 321.) Amygdules, and variations in grain and probably variations in chemical character are also more symmetrically arranged in intrusions.

(2) We have shown above (Chap. V) that in so far as we may assume (a) that an intrusive sheet heats up its walls while an effusive sheet has them kept at a fairly constant temperature,* or (b) that an intrusive sheet is at a temperature much above that of solidification, while a flow comes down more nearly thereto, before ceasing to flow and solidifying at rest,† or (c) that the walls of an intrusive sheet tend to check the escape of gases whose escape promotes solidification ‡ the effusive rock, so far as the grain of its last formed constituents is concerned, will have a marginal zone of finer grain, which may extend to its center, but which will be narrower or wanting in the intrusive rocks, —in the plutonic rocks generally wanting. It may be wanting if the upper part of an effusive has been eroded away.

(3) If as above assumed we suppose the effusive magma to continue to flow as long as possible, there will be a larger proportion of crystals which will be formed during the period of motion and will show this by their fluidal arrangement, mechanical fractures, etc. (porphyritic texture).

(4) Gas bubbles cannot form under too great a pressure. Hence the vesicular (altering to amygdaloid) texture cannot be formed at too great depth. This texture also implies glass. Generally amygdules are rare or absent in intrusions. In flows they are characteristic, often very abundant in the upper part, less so at the bottom of the flow where, however, elongate spike amygdules often occur at right angles to the contact.

* That the former condition is often true is shown by the baking effect on the rock outside. That the latter condition is also approximately true is also shown by the fact that lava fields have been walked on while the temperature a few feet below was glowing.

† The former part of this statement is suggested by various facts as to initial temperatures of lavas, e. g., the fact that the lava boiling up in Kilauea melts down the crust, while the latter part is obviously likely.

‡ As the flow of gases follows the same laws as that of heat, the effect is the same as that of hypothesis (a), or if the walls are already saturated with gases or steam, it is equivalent to raising the temperature at the margin (i. e., having a hotter country rock) so far as this effect is concerned.

(5) The production of glass requires a rapid cooling down below the temperature of solidification of the last mineral which would have been formed in case the rock had been able to crystallize completely. Hence if the walls of a sheet were not kept cold glass would not be so likely to form. In other words even near the margin intrusive rocks are less likely to be glassy.

(6) Toward the center of the flow or wherever the cooling was slow enough to allow complete crystallization to take place, in an effusive complete crystallization might take place until there was nothing but gas in the interstices (porous miarolitic, microdrusic or doleritic texture). These cavities might remain empty, or be filled in the ordinary way with secondary minerals of the zeolite or chlorite groups, or chalcedony or opal, etc., permeating the pores. In an intrusive rock such crystallization would be likely to go on until in the interstices there was a hot water solution of alkaline silicates and silica, which might circulate and react on the minerals previously formed, or be deposited in veinlike manner as micropegmatite. Such cavities could certainly not be empty, i. e., filled merely with gas, unless the intrusive were so near the surface that the pressure was not sufficient to keep superheated water in the liquid state. Thus there should be a difference between effusive and intrusive rocks, in the filling of the last interstices. (7) Furthermore, the retention of any gas, whether steam or other mineralizer, might be expected to somewhat modify the minerals that would be formed in the crystallization of a magma. Iddings (U. S. G. S., Twelfth Ann. Rep., p. 657) has studied this feature in a somewhat less basic group of rocks. The most essential difference that he found was the greater development of biotite and quartz in the intruded rocks. Hornblende instead of augite he also notes. Something similar may perhaps be noted in our rocks, for in the diabases, intrusive rocks, there is more marked zonar variation of the feldspar, and the quartz, though absent in the effusive equivalents, appears just as in the dioritic series which Iddings studied.

(8) Finally, there are differences in the relative sizes of the various constituents, which may be significant. The feldspar in the dikes seems

to be generally larger in proportion to the augite than in the sheets,* and this fact may be connected with the probably hotter initial temperature which we have suggested above for the dikes. For in that case the feldspar might get more of the benefit of the slow initial cooling, as may be seen by a study of Plate IV.†

We have given a number of characteristics of intrusive rocks. Not all these characteristics may exist in a given intrusive, for here as everywhere there are transitions. Nor is there any one characteristic by which we can identify every fragment of an intrusive basic rock. The interior of a large flow is not often glassy. The margin of a sufficiently small and sufficiently shallow intrusive may be. It will probably be well in time to replace the expression "characteristically intrusive", if the above definition is nearly acceptable, by the characteristics of texture or composition which we find most uniformly to indicate intrusive character, but it is hardly well to let the discussion of nomenclature blind us to our real object, which is to determine from the characteristics of a rock its origin and environment.

We pass then to the descriptions of the sections of the diabases to see how far we can recognize the characters above stated.‡

§ 3. Basic dike rocks. General description.

In these rocks a lime-soda feldspar whose cleavage faces show the well known twinning lines, lies in lath shaped forms running in every direction through a dark brownish gray to black mass, which the microscope shows is mainly composed of pyroxene. They are the youngest igneous rocks of the iron region, and cut every formation so far as known, excepting the Eastern (Potsdam) sandstone. They correspond closely with many of the effusive forms which we find in the Keweenaw series.

In the region about Marquette they run nearly east and west and cut the serpentine.

These rocks were probably included by Foster and Whitney in the correct general designation "trap dykes".‖ Koch§ as early as 1852

* With the exception of the peculiar irregular streaks of doleritic texture in the sheets, excluding also crystals plainly formed before the magma came to rest.

† The zone of uniform grain of the dikes, Fig. 17, shows that the initial temperature being $0.784 = \widehat{n}/4$, the temperature of formation of augite must be somewhere between 0.600 and 0.250. If the temperatures of formation of the feldspar were in the interval between 0.784 and 0.600, the time of its formation between these temperatures might be much greater relative to the time of passage through the range of temperatures devoted to the formation of augite, than if the latter were nearer the initial temperature. However, we cannot say that this is the only factor concerned, for the feldspar in the diabases seems to have continued to grow longer than in the flows, changing its chemical character.

‡ It may be well to remark that the order of investigation was the reverse. The descriptions were first written.

‖ Foster and Whitney, II, p. 19.

§ Studien der Goettingischen Verein Bergmaennischer Freunde, 1852, VI, p. 201.

recognized that these traps were composed essentially of augite and labradorite, with a certain amount of magnetite generally associated in minute grains, and called them dolerite. This is almost equivalent to the name that we call them, the difference between dolerite and diabase being according to Rosenbusch one of age, and Rominger has retained the name dolerite.*

In the meantime, however, Brooks and Marvine had taken a step in the wrong direction, afterward corrected by Wichmann, Allport and others,† by calling amphibole what was really augite, so that these rocks became "trappean diorite".‡

Wadsworth contemporaneously with the Wisconsin report recognized these rocks as diabases§ and they have since been generally accepted as such by Irving, Williams, Van Hise, and others who have written on them. The subdivisions that I have found it worth while to make, in my larger material, have not been made by previous writers and are perhaps too minute. By far the largest number of the dikes of this group belong to the quartz diabase type (a term which Wichmann used) of which the others may be considered exceptional modifications.

§ 4. Enstatite diabase.

This peculiar type is known from only one locality, i. e., from a rock point on the west side of the big bay, Sec. 4, T. 51, R. 27. It is called trap in the field note book and appears to be from a dike cutting the granite represented by Sps.¶ 698, 699. Sp. 693 is immediately from the contact and the others follow in the order indicated by their location. The south limits of the trap are covered with recent formations. This outcrop has not been studied enough to determine its geological relations, so as to know whether it is merely a modification of the quartz diabase group, as appears most natural, or of the peridotites. Wright named it serpentine.

Enstatite or bronzite has also been found rarely by Van Hise (U. S. G. S., Mon. XIX, pp. 350, 351, 354) in the diabases of the Penokee district.

The hand specimens are much alike and in general look like an ordinary diabase of fair freshness, except that here and there, not too

* Geol. Sur. Mich., 1880, IV, p. 145, et seq.

† Geol. Sur. Wis., III, 1879, pp. 570, 621–627.

‡ Geol. Sur. Mich. II, 1873, pp. 42, 51, 158, 176 to 179.

§ Bull. Mus. Comp. Zool., vii, 1880, pp. 36, 39.

¶ S., respectively Ss., is used to denote reference to rock sections, Sp., respectively Sps., to denote reference more particularly to hand specimens.

abundantly, are sprinkled small crystals of enstatite of a yellow brassy lustre.

The ground is of a dark gray color and the feldspar crystals do not show much variation in size, being between one and two millimeters long and of the form and habit usual in diabases.

The specimens from this dike are all located from the S. E. cor. Sec. 4, T. 51, R. 27, as follows: 692, 1685 paces N., 645 paces W.; 693, 1800 paces N., 660 paces W.; 694, 1675 paces N, 625 paces W.; 695, 1620 paces N., 620 paces W.; 696, 1606 paces N., 640 paces W.; 697, 1600 paces N., 650 paces W.

NOTES ON THIN SECTIONS.

S. 692 is composed of chlorite, magnetite, plagioclase, with small interstices filled with quartz.

S. 694 shows plagioclase enclosed in augite, the augite often twinned. A pinacoidal cleavage is often developed in the augite.

S. 693 is of the same general type. The section is all ground to pieces.

S. 695 is also ground to pieces, but shows some well characterized leucoxene pseudomorphs after iron oxides.

S. 696 is one of the best sections for study. In it the augite is much fresher than in some of the others, and is often much twinned parallel to (100). A pseudo-diallagic parting parallel to the basal plane (001) is often developed. The extinctions of the feldspar vary from center to margin. Symmetrical extinctions near the center are 31°-33°† with 16°, Karlsbad twinning, and Baveno so superadded that the sections cannot be very far from perpendicular to the zone (010-001). Another double twin has 15°-12° with 32°. Another with 31°-29° seems to be also a double twin with the two albite twins of the other half of the Karlsbad twin having the same angles. Another has 37°-41° with 19°, another 36½°-41° with 21°, another 19°-39°, another 38°, etc. These indicate a somewhat more basic feldspar, but as a whole the angles point to the labradorite Ab_2An_3 as the variety of feldspar. Quartz occurs in the interstices.

S. 697 shows interstitial quartz, enstatite, diallage (?) and plagioclase.

The coarseness of grain in this rock is similar to that in the other diabases.

§ 5. Olivine diabase.

The next group that we make are close akin to the following group of quartz diabases. Yet they are not quartz diabases, and in the quartz diabases the olivine appears to me to be only accessory. Wichmann found no olivine.*

*Geol. Sur. Wis., III, 627.

†Throughout this chapter angular measurements of extinctions connected with a dash are the extinction angles of feldspar lamellæ twinned according to the albite law When lamellæ twinned according to the Karlsbad law are also present they are joined by a bracket or the word "with."

Wadsworth found it abundant (Bull. Mus. Comp. Zool., July, 1880, VII, p. 70), G. H. Williams (U. S. G. S., Bull. 62, p. 197) seems to have found it abundant, and classes as an olivine diabase the Lighthouse Point dike, which from its accessibility and frequent description I take as the type of the quartz diabases. Olivine is certainly not at all rare in the quartz diabases but in quantity insignificant, probably irregularly disseminated and without any effect on the texture that I can see (Cf. Van Hise, U. S. G. S., Mon. XIX, p. 350). However, as just remarked, the two groups are in this region closely allied.

To the olivine diabases I assign the following thin sections:

Ss. 808, 828, 11860, from a two-foot dike striking across Presque Isle;

Ss. 11421, 11422, 11423, 11424, 11425, 11426, from South Island in Sec. 2, T. 48, R. 25;

Ss. 11489, 11490, from Middle Point, Sec. 3, T. 48, R. 25;

S. 11827, S. 12180, S. 12179, S. 9085.

See also dikes 61 and 175, described by Wadsworth (*loc. cit.* pp. 40 and 42).

In these sections even in the coarsest grained central rock there is but a trace of micropegmatite, instead of which (Ss. 11489, 11421, 11422, 11426) the texture is often ophitic,* i. e., the feldspar is embedded in

*It is to be noted that I use the term ophite, ophitic, as I have heretofore, i. e., in accordance with its original definition and in a narrower sense than it sometimes has been used.

Michel Lévy is responsible for the introduction of the term into petrography, and we take the definition from his "Structures et Classification des Roches Éruptives, p. 26: "Quand le dernier élément consolidé est un bisilicate (generalement pyroxénique), ses plages, sans contours extérieurs propres, sont lardées de cristaux plus anciens; ceux de feldspath notamment s'allongent suivant l'arête pg[1] (001) (010), ou s'aplatissent suivant g[1] (010), et l'ensemble prend une apparence caractéristique que j'ai décrite et déssinée dès 1877 sous le nomme de structure ophitique."

In this definition there are three points, first, that the pyroxene component is last consolidated, second, that it occurs in areas which are larded, as meat is larded for cooking, with streaks of older crystals, and thirdly that these crystals are much flattened or elongated. Vélain, for example, in his Conférences de Petrographie, p. 59, speaks of the ophitic texture as characterized by the elongation of the feldspathic element, and its distribution through the areas of the ferruginous element (pyroxene). But it has often happened that only the first or third point has been taken to be essential to the definition. Lapparent (Géologie, 1883, p. 630) alludes to the tendency of the feldspar to form elongate crystals as characteristic of the ophites, but his figures and descriptions show the areas of pyroxene in which they are embedded. We find that in their experiments on the reproduction of rocks, Fouqué and Lévy apply the term ophite, not to all rocks having elongate feldspar or xenomorphic pyroxene, but to those only that have the structure above described.

For the German use Rosenbusch (Mik. Phys. ii, 1887, p. 191; 1896, pp. 1114, 1009) distinctly includes the "large allotriomorphic augite individuals" as part of the meaning of the word, as is also apparent from his figure of the ophite structure (Plate ii, fig. 3, but not fig. 4, as will be seen by his description of plates), classing it as a variety of his intersertal, or diabasic structure. Among others who use the term in the narrower sense may be noted Rutley in "Granites and Greenstones", Harker in his Petrology, Judd in Q. J. G. S., 1885, p. 360, 361, 1886, p. 68, and Wadsworth, Minn. Geol. Sur. Bull. II, p. 107, while among those who use or define it in a broader sense are Zirkel, Kemp, Williams (in Standard Dictionary and Bull. 62, U. S. G. S.), and Loewinson-Lessing. But in its broader sense we have a couple of synonyms, diabasic, and intersertal, and when used in its narrower sense as applicable to that texture that produces the lustre-mottled effect, the etymology of ophite becomes strikingly appropriate. Plate VII, reminds one at a glance of the marking of many snakes. Of course, however, the determining factor is the usage of its distinguished sponsor.

patches of augite, between the limits of which corroded granules of decomposed olivine are crowded. At other times there are irregular smaller xenomorphic granules of augite wedged in between the feldspar. They are thus like the ophite melaphyres, Pumpelly's lustre-mottled rocks, which are so abundant in the Keweenawan.

The FELDSPAR seems more basic than in quartz diabases but is relatively larger than in effusives, except in the doleritic seams of the ophite. One section, S. 11860 = S. 828, contains porphyritic crystals of anorthite, with symmetrical extinctions greater than 45°, while symmetrical extinctions running up to 45° are not uncommon, so that the feldspar would be often classed in the bytownite or anorthite series, being over two-thirds anorthite. This applies to the most basic part only. Zonal extinctions occur as in the quartz diabases, if not quite so marked. Extinctions do not seem so high in marginal sections as in sections from near the center of the dike.

The patches of AUGITE are brownish, and show traces of pinacoidal cleavage, (S. 11827). They are very fresh.

OLIVINE is quite abundant. It is often highly idiomorphic, or in the corroded grains already mentioned. It is often heavily coated with iron oxides, and sometimes changed to chlorite and mica serpentine, or in S. 11860, apparently to talc.

The IRON OXIDES occur much as in quartz diabases. In the coarser grained forms (Ss. 11421, 11422) they occur in large angular, irregular or octahedral grains, which are distinctly moulded upon and hence of later origin than the feldspar. Accordingly they occur in the ophitic patches of augite, but not in the feldspar, the order of crystallization being olivine and anorthite, then magnetite, then augite. At the margins of the dikes there is a glass which tends to have a mottled appearance, and is heavily dusted with iron oxides, sometimes in growth-forms. (S. 828.)

No APATITE was distinctly recognized.

One yellow isotropic cube was visible in S. 11420, which may well be PEROVSKITE, but is possibly PICOTITE.

It will be seen that the rocks considered have a sufficiently distinctive character to be treated separately from quartz diabases. The tabulation below shows the variation of grain in one dike in sections taken at known distances from the margin, and also some observations of the extinction angles of the feldspars.

These observations on the grain are plotted in Fig. 17.

It is not merely accidental that the ophitic texture is associated in these olivine diabases with the more basic feldspar, greater amount of olivine, and generally more basic character. Fouqué and Lévy's experiments have shown that the ophitic texture is most easily formed in the more basic rocks and the same experiments show that the nearer anorthite a feldspar is, the higher the temperature at which it forms. Now the ophitic texture is dependent upon the feldspar being formed distinctly before the augite, so as to be enclosed in it. The occurrence of an ophitic texture is then a sign of a basic feldspar and the basicity of the feldspar is something of an indication of the basicity of the rock. The texture is not, however, solely dependent upon that. It requires also that the rock should be in a state of rest when this texture was formed, and that the rock should first cool through the temperature of

No. of specimen.	Distance from margin.	Character of feldspar.*	Diameter in millimeters of sections of—			
			Feldspar.	Augite.	Magnetite.	Olivine
11421	10 paces from N. E. side, i. e. 26 ft.	{22°-36° 11°} 28°-39° 45°-45° {21°-49° 17°-44°} {13° 41°-40°} {20° 35°-20°} 46°-52° 37°-21°	1.56 x 0.125 1.34 0.156 2.03 0.156 Av. 1.64 0.146	4.06 5.94 Av. 5.0	0.28 0.21 0.81 0.62 0.53 0.62 Av. 0.58 x 0.46	
11422	10 paces from S. E. i. e. 26 ft.	28°-28° 11°-12° 35°-35° 33°-35°½	0.93 x 0.31 1.88 0.16 1.06 0.37 1.25 0.21 1.22 0.15 Av. 1.27 0.24	3.75 3.75 1.69 0.76 3.12 2.97 2.19 1.56 Av. 2.05	0.34 0.81 x 0.75 0.41 0.53 0.94 0.75 0.53 0.38 0.87 0.62	0.40
11426	5 ft. from S. E. contact.	25°-29° 27°-20° {45°-45° 15°}	1.16 x 0.12 1.56 0.25 1.34 0.28	1.87 1.56 2.09	0.69 x 0.62 0.22 0.06 0.53 0.46	
11425	2 ft. from contact.	26°-25°; 31°-33° 35°-28°; 21°-18°	1.25 x 0.15 1.41 0.16 0.78 0 94	1.25 0.73 1.40	0.47 x 0.38 0.31 0.22 0.28 0.22	1.25
11424	near contact.	21°-22°	0.78 x 0.12 0.78 0.06 0.94 0.05	0 25 x 0.19 0.31 0.16 0.25 0.16	0.15 0.12 0.19	0.46
11423	N. E. contact.	2[illegible]°-25° 18°-7°				
11420	Porphyritic. Total width about 18 paces or 47 feet.	50°-39° & 39° in a Baveno cross	0.38 x 0.06 0.62 0.06 0.87 0.13 smaller 0.32 to 0.37 x 0.03	0.12 x 0.12 0.06 0.09	0.02 to dust	0.25 0.19

* Extinctions of lamellæ connected by the albite law are separated by a dash. Those connected by the Karlsbad law are grouped in brackets.

feldspar formation, and then pass fairly slowly through the temperatures of augite formation, i. e., the brighter red heats.

Hence the ophitic texture cannot date back of the period of final rest and requires that the rock shall be of a certain basicity, above but not too much above a bright red heat, at the beginning of solidification, and shall thereafter cool slowly and quietly. Hence it is that we do not find the ophitic texture at the margin, and (see below, § 6) in cases where the center of the dike grows markedly more acid the ophitic texture is confined to a zone at a certain distance from the margin.

Finally, as will be seen by reference to our descriptions of extrusive rocks, the ophitic texture seems to be more abundant in the flows than in the corresponding dikes. This may be due to the fact that when the rock had cooled down to red temperatures the absorbed gases had no considerable role to play in the flows, while in the dikes they helped to prolong the feldspar growth, making it more continuous and less sharply antecedent to the augite, and furnishing a magma in which both feldspar and augite formed.

It is obvious too from Pl. IV, that the time of augite formation would be longer if the initial temperatures of cooling were only just at or above the temperature of augite making, than if it were a little higher, and that may have something to do with it.

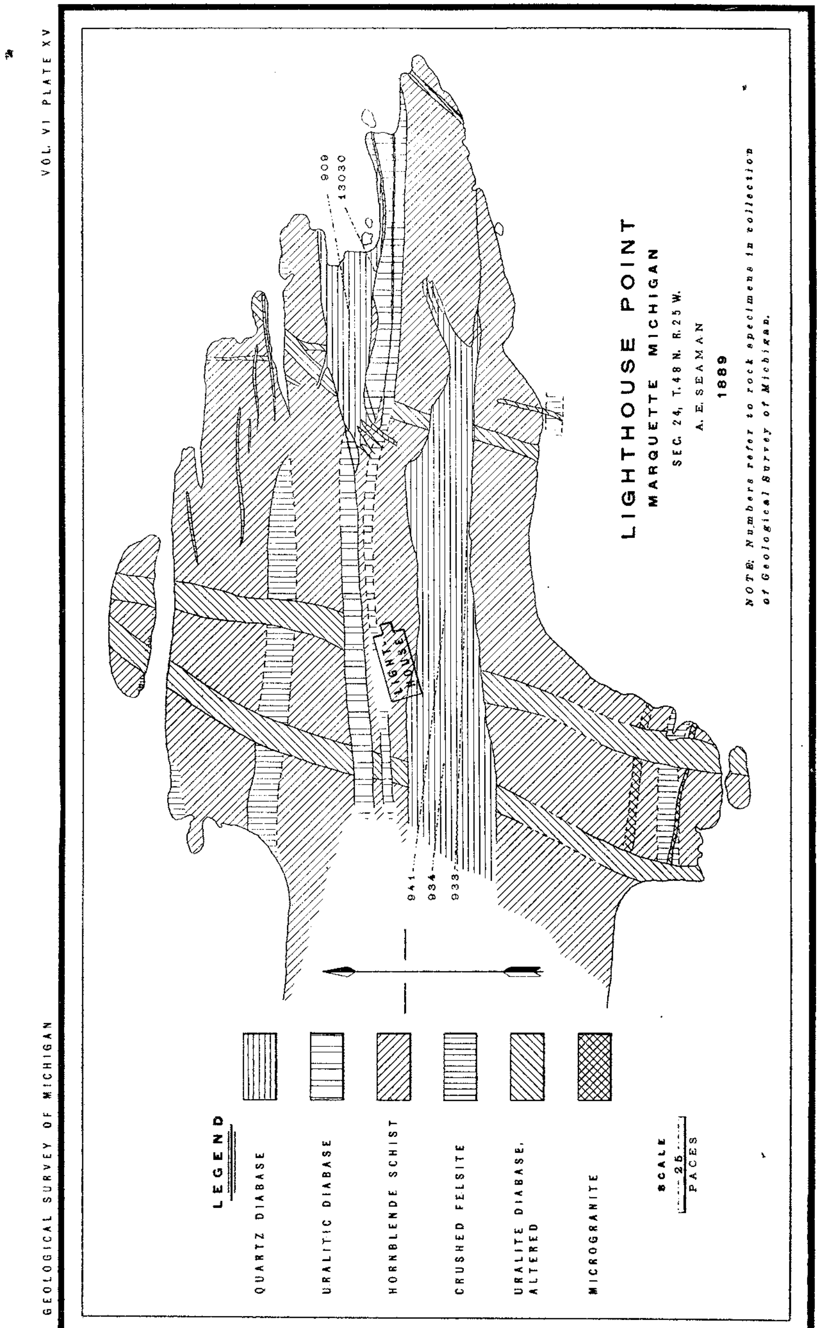
§ 6. Quartz diabase.

It must not be understood from the name applied to this group of rocks that quartz is a very prominent feature to the eye, for it is not. Only in comparison with other diabases is the quartz characteristic, for it is generally entirely microscopic. There are however a number of other characters, one or another of which is always present, that serve to distinguish rocks of this group very fairly, even to the naked eye. They have often been partly described.*

As a type we will take the great dike at Lighthouse Point, T. 48, R. 25, mentioned by Rominger,† Williams and Wadsworth. From various parts and outcrops of this dike the Survey has seventeen sections, and G. H. Williams had nine more which I have been kindly permitted to see, and several more, through Prof. Seaman and Mr. Sutton, from the collection of the Michigan College of Mines, so that we have a good

* Williams, Bull. U. S. G. S., No. 62, 1890, p. 138; Wadsworth, Notes on the Geology of the Iron and Copper districts of Lake Superior, 1880, pp. 36, 37, report of State Geologist, 1891-92; Rominger, Geol. Sur. Mich., IV, Ch. VIII; V, Pt. I, p. 6; Bayley's description U. S. G. S., Mon. XXVIII, came to hand while this volume was going through the press. See the footnote at the end of § 9.

† Geol. Sur. Mich., IV, pp. 146-147.



chance to observe the range in its character, viz., coarse and fresh: Ss. 11763, 869, 871, 909, 934, 941, 947, 965, 8148, 11617 (W)*, 11622 (W), 11636 (W), 11666 (W); fresh, fine grained marginal forms, 966, 933, 875, 949, 962, 11762, 11621 (W), 13030; coarse but altered, 948, 910, 11672 (W), 11675 (W), 11615 (W); both altered and fine grained, 11616 (W), 11617 (W).

Beginning in our study with the coarsest and freshest specimens, from the interior of the dike, not crushed nor weathered, we find a rock which to the naked eye appears fresh and glassy in lustre, neither silky nor as dull as are hornblende rocks. The color is dark gray, not greenish in tone, specked with white facets of feldspar, on which with a lens the twinning striations can be easily recognized, and the facets are elongate parallel to these striations. A negative character is the practical absence of that texture which from the appearance of flashing spots when the specimen is turned around in the sunlight has been called ophitic, lustre mottled, or poikilitic. (See pp. 48, 127.) This character is important in separating them from the olivine diabases and ophites. Under the microscope we see that the rock is made up of distinctly lath-shaped labradorite, of brownish augite and of opaque iron oxides. Accessory and embedded in the augite is often a little olivine, more or less altered, and there are always little interstitial spaces, which in the hand specimen appear as minute reddish specks, in and around which occur quartz, feldspar of the acid varieties, brown hornblende, mica, etc., as hereafter described. Neither olivine nor these "acid interstices," as we shall call them, appear to form any great part of the rock, but the latter are uniformly distributed and quite characteristic.

The LABRADORITE shows complex twins according to the albite law, which gives twin lamellæ with boundaries nearly parallel to (010), sometimes zigzag (S. 11828); combined with Karlsbad, pericline, Baveno and probably other laws. The Karlsbad law combined with the albite produces three or four sets of lamellæ parallel to (010) with different extinction angles, and no position in which all the bands or lamellæ are equally illuminated. The pericline law produces lamellæ which in the zone of symmetrical albite extinctions are at right angles to the albite lamellæ. The Baveno law produces cruciform cross-sections and in general stellate groupings, since the feldspar is developed in tablets parallel to (010). The extinctions can be symmetrical for the albite lamellæ in both parts of a Baveno twin only for a particular section, such as was encountered in S. 11484. The extinction is dispersed, so that between

* (W) affixed to a number denotes that the section and number are of the Williams collection.

cross-nicols a distinct change from bluish to brownish is noticeable on passing through the position of greatest darkness. Careful study of a section almost perpendicular to the positive bissectrix in S. 11801 led to the diagram, fig. 27, illustrating the approximate position of the optical constants, which agrees very well with Lévy's diagram for Ab_3An_4 in the "Détermination des Feldspaths." (See also S. 909.) The dispersion of the extinction is easily noted in the bluish tinge outside and brownish tinge inside, of the dark zone of the feldspar in case it is turned so that the center is beginning to get light while the margin is not yet dark. It also varies from center to margin in such a way as to indicate a decreasing percentage of lime toward the margin, and the

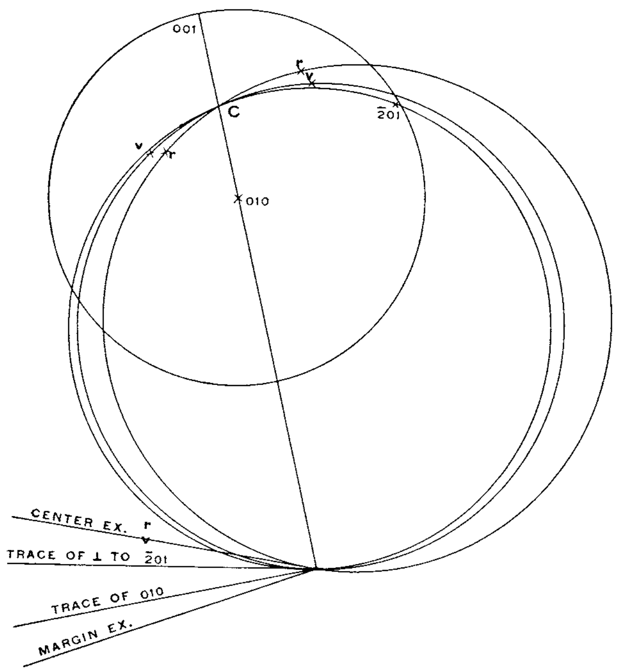


FIG. 27

Stereographic projection (see p. 40) upon the lateral pinacoid, i. e., m (010), of labradorite, showing the positions and dispersion of the optical axes.

margin is often continued out into pegmatitic intergrowth with quartz. In such case its relative refraction (see below, § 9) shows that it is orthoclase or albite. Twinned crystals cut nearly perpendicular to the lateral pinacoid (010) show nearly symmetrical extinction angles, generally between 20° and 30°. The extinctions tabulated below* show that, e. g. in S. 941, the centers of the feldspars must be in composition between Ab_1An_1 and Ab_2An_3, which agrees with the analyses made for Van Hise.

* As before, Albite connected by –, Karlsbad by brackets.

T. 48, R. 25		Averages			
11484	24°–18°		11878	30°–37°	33°
Margin	14°–20°		769	15°–23°	
	19°–23–				
	27°–20°			26°–24°	
Baveno twins, angle between arms of cross 83°	22°–22° }			20°–30°	
	21°–19° }			{ 26°–32°	
		21°		{ 0°	
					22°
11485	22°–24°		11763	23°–24°	24°
Center	20°–12°				
	42°–34°		869	32°–30°	31°
	25°–31°				
	20°–21°		941	{ 38°–32°	
		25°			
11735	{ 31°–32°			{ 11°–11°	
	{ 13°			{ 12°–12°	
Margin	24°–23°			{ 38°	
	{ 29°–30°		875	17°–17°	
	{ 13°			37°–35°	
	28°–35°	26°		37°–35°	
					26°
11750	28°–24°				
Center	{ 26°–31°		949	30°–32°	31°
	{ 16°				
	27°–31°				
	18°–19°				
	25°–31°				
		25°			
11801	up to 30°				
11807	25°–28°				
Margin	26°–25°				
	23°–23°				
	23°–27°				
	24°–30°				
	19°–22°				
	26°–26°				
		24°			
763	up to 30°				
767	not up to 30°				

Comparing the extinctions with those observed by Irving in the "Copper-Bearing Rocks"* we see that they are nearest to the extinctions of the feldspars in his olivinitic and lustre mottled rocks. Enclosures of glass, iron oxides, etc., in the feldspars are more common in the marginal forms.

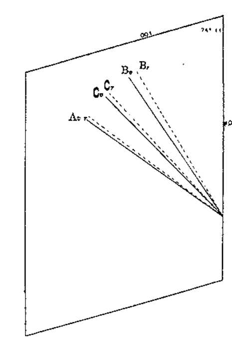


FIG. 28

Projection on m (010) of the optical axes of augite.

The AUGITE is in thin section very light pinkish brown, parallel to (100), lighter and more yellow perpendicular to it. The optical angle is small, the dispersion r>v is stronger for the axis which is more nearly parallel to the prism axis as shown in Fig. 28 (S. 13749). The pinacoidal cleavages are sub-

* U. S. G. S., Mon. V, Chap. III.

ordinate to the prismatic, but there is often a twinning on the front pinacoid and sometimes a basal twin striation or twin lamellation is visible (S. 844). The augite is not commonly idiomorphic, but may be so against the acid interstices (S. 909), then showing the forms of an octagonal prism with the pinacoids more developed than the prisms (S. 778). Sometimes it is surrounded by a border of brown hornblende. Occasionally the augite has an odd rounded growth, which suggests at once the origin of the hornblende crystal described and figured by Williams.*

A series of augite crystals seem to have started growing outward from a center in various directions, all having the clinopinacoid (010) parallel. The lines between them are irregular, and no definite twinning law can be made out, though they remind one of the "knäuel-artige Verwachsungen" mentioned by Rosenbusch.† The angle between the vertical axes of successive parts seems to be very small.

The OLIVINE is distinguished from the augite by its more nearly colorless, or its greenish hue, and greater decomposition especially along the cracks which are largely pinacoidal. In favorable cases it can be determined that the optical angle is larger than that of augite. In form the olivine is either

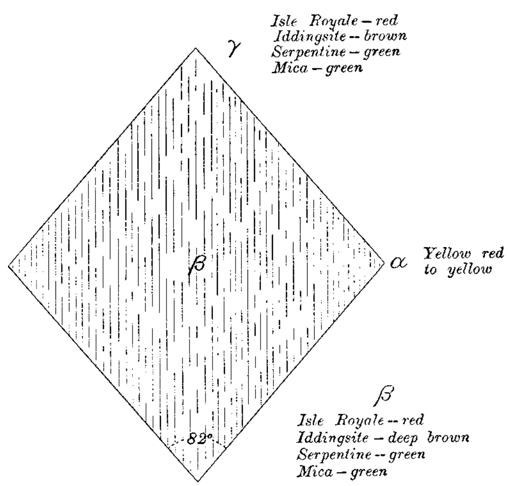


FIG. 29

Illustrates the comparative pleochroism of micaceous alteration products of olivine.

rounded or terminates with angles not far from 90° (82°). (Fig. 29.) Even when the grains of olivine show no crystal form, their outlines are not determined by other minerals, i. e., xenomorphic, but rather suggest corroded fragments which are commonly embedded in the augite, rather than the feldspar. They are most sharply idiomorphic near the margin.

The grains of iron oxide in reflected light show sometimes a bluish lustre, when we call them MAGNETITE; sometimes a dead black lustre, when we

* U. S. G. S., Bull. 62, p. 183, fig. 28. Compare Lawson's polysomatic augites.

† Mik. Phys., I, 1892, p. 513, and Pl. XVIII, fig. 5.

call them ILMENITE. The ilmenite has been observed surrounding a magnetite centre (S. 947), or traversing it in streaks (S. 965). The iron oxide grains are often irregular, and not idiomorphic against the feldspar, but occur sometimes also in octahedral forms, especially in those skeletal forms which are due to rapid growth, as in S. 11763—near the margin.

More or less abundant are the ACID INTERSTICES (Pl. XVI), against which the feldspar is generally, the augite and magnetite often, idiomorphic, although the augite is often bordered with brown hornblende (S. 869).

BROWN MICA also occurs associated with the iron oxides, often having its basal plane applied to the face of the iron oxides, and so occurring with them as to indicate a genetic connection.*

The BROWN HORNBLENDE just mentioned is not the same as the ordinary green uralite by any means, in fact may be also turned green at the same time that the augite is uralitized. Yet it interdigitates with, and runs into, the augite in a way that shows plainly that it is derived from it. It has also been noted by Irving and Van Hise.

From the feldspar laths growths of micropegmatite often spring out, the feldspar of which is continuous with the acid margins of the feldspar. There are also in these interstices independent grains of quartz? They are traversed by long apatite needles, hexagonal and idiomorphic. They are rarely if ever so fresh as not to be clouded over with a reddish ferruginous dust, and not to contain small folia of brown and green mica (S. 965).

The micropegmatite growths are illustrated in Pl. XVI from S. 7931, one of the diabase granophyrite group.

A proper understanding of these interstices, which appear to be the same mentioned by Rosenbusch, Mik. Phys. II, p. 194, ed. of 1887; 3d ed., 1896, pp. 1117, 1140, 1143–1146, 1149, 1307, and of their origin seems important yet difficult. Wadsworth † and Irving ‡ take micropegmatite to be a secondary texture, replacing feldspar, etc., and Williams § seems to consider this interpretation possible. Says Wadsworth, speaking of some Minnesota rocks:

"In the earlier stages of alteration of the groundmass or feldspar there arises a confused mass of viridite, ferrite, magnetite, quartz grains, feldspathic material, etc. As this alteration progresses the tendency is to assume a radiated fibrous structure or else an imperfect graphic form. Further changes in the rock results in the quartz taking upon itself a true graphic form, the same as that seen in graphic granite, while in still further changes the quartz is in

* Kemp, Bull. Geol. Soc. Am., V, 1893, p. 220; Williams, *loc. cit.*, pp. 139, 140; Wadsworth, Minn. Geol. Sur., Bull. II, pp. 64, 65, and farther references given there; Cf. also C. H. Smyth, on biotite and magnetite reaction rims, Trans. N. Y. Acad. Sci. (May 21, 1894) XIII, p. 213.

† Minn. Geol. Sur., Bull. II, pp. 67, 68, 81, 103, 109.

‡ Copper-Bearing Rocks of Lake Superior, U. S. G. S., Mon. V, 1883, plates v, xii, xiv, xv, descriptive text.

§ U. S. G. S., Bull. 62., p. 141.

rounded or irregular forms in the midst of the altered reddish-brown feldspathic material. The pyroxenic element in the meanwhile has been altered to biotite and hornblende:—"

In this view of micropegmatite in which Wadsworth was at first almost or quite alone, he has been finding more and more followers,* and as my own observations do not agree with them, but rather with Rosenbusch, but point to other, theoretically and practically very interesting conclusions, I will give them very fully.

In this discussion, in order to have a broader basis to eliminate subjective statements, and put results in numerical form, we will not confine ourselves to the Lighthouse Point dike, which is nevertheless a very good example, nor to the quartz diabase group, but include all the specimens of diabasic dikes more recent than the greenstone schists, from townships 48 and 47, ranges 25 and 26. We will also include the sections from the same region described by Williams. There are also some described by H. B. Patton. In all we have some 245 specimens to study, including some altered porphyrites and uralite diabases which may in part represent weathered forms of this group, but I feel sure also represent other distinct igneous formations, yet not including rocks so far changed as to rank with hornblende schists.†

In the first place these micropegmatite growths do not generally seem to replace the feldspar, iron oxides or augite. Each of these is at times idiomorphic against them. The occurrence of reddish pigment and folia of green mica suggests that glass has been replaced. They do not occur, however, at the glassy margins of dikes, and when decomposed glass occurs there it has a very different appearance and I have not seen any transitions between glass or decomposed glass and micropegmatite. In fact the most convincing sign of the nature of the micropegmatite lies in the fact that it has mutually exclusive relations with textures that are undoubtedly primary and sometimes occur in other parts of the same dike. The poikilitic or ophitic texture occurs seven times in the fresh non-uralitic specimens. In no case is micropegmatite mentioned as associated. In uralitic diabases or porphyrites a poikilitic texture is mentioned nine times, but only in one case is quartz, which is distinctly said to be secondary, mentioned as occurring with it,—in no case micropegmatite. Grouping together specimens distinctly mentioned as

*Cf. Bayley in U. S. G. S., Mon. XXVIII, p. 520, and foot note at the end of § 9.

†I do not include in my statistics the sections from Bayley and the Michigan College of Mines, as they were selected to show the micropegmatite and have not the same objectivity.

marginal in the field notes with those which by their glass,—fresh or altered,—porphyritic and microlitic texture or characteristic iron oxide growths betray themselves as originally glassy marginal rocks, we find 57 of them. In 32 the augite is quite fresh, and in only one is micropegmatite said also to exist. This—S. 11750—proves on revision to be one in which a little decomposed glass was suspected to exist in the mesostasis while in other parts the interstices were granophyric, and is no real exception. In 9 of the uralitic or chloritic ones (9 out of 24) quartz is mentioned as occurring, but not once micropegmatite. The quartz is often distinctly stated to be secondary, not interstitial at all, and in other cases the existence of the altered glass is dubious, but that my observations might be surely impartial I have not revised them with this question in mind. The micropegmatite being, therefore, thus mutually exclusive with glass and poikilitic texture must be itself a primary texture or replace one.

Now as to its relations to uralitic and chloritic changes, we find micropegmatite in 13 out of 62 fresh basic dike rocks (20%); in 18 out of 149 uralitic ones (12%); in 3 out of 41 chloritic ones (8%).

The percentage of rocks observed to contain micropegmatite decreases with their alteration, and this indicates clearly that it is the result of some process different from the change to uralite or chlorite. If, as we properly ought, we subtract from these figures the number of sections which have textures exclusive of micropegmatite, the results would become still more striking, for in fact *all the fresh, neither ophitic nor marginal, sections are recorded to contain micropegmatite*, except—

S. 11490, which is from a dike elsewhere ophitic, and tends itself to be porphyritic,

S. 11708 (W) a small dike (Williams does not mention glass, but my sections from the same dike show it),

S. 11485, not altogether fresh,

S. 845, which is only two feet from the edge of a dike that elsewhere has micropegmatite,

And a number of Williams's sections, e. g., from the Lighthouse Point dike, in which he says, however, that primary quartz does at times occur, viz.: 11617 (W), 11622 (W), 11636 (W), 11666 (W) and 11814 (W).

Finally we have S. 11811, from an east and west diabase dike about 30 feet wide, near Dead River, 1180 paces N., 1250 paces W., Sec. 10, T. 48 N., R. 25 W., in which instead of acid interstices we have a mesostasis full of sheaves of feldspar microlites as described in Rosenbusch.* This is, therefore, the one real and decided exception to the rule that the central parts of large basic dikes which are not ophitic contain micropegmatite. But if micropegmatite occurs in practically all the fresh central non-ophitic specimens, it occurs in but about 16 out of 78 of the central, non-ophitic, but uralitic specimens of the diabases, and in 3 out of 16 chloritic ones. This I believe to be due to its obliteration in the processes of uralitization, weathering or crushing, but it may also be conceived to have originally occurred more in the youngest set of dikes. If, moreover, the micropegmatite were due to mere weathering, the absence of micropegmatite in the Keweenawan flows of similar character would be unaccountable.

The extension of these numerical comparisons to all the dikes collected in the Upper Peninsula would only strengthen our results. The role of apatite is well indicated by the fact that out of 52 times that it is noted it is 8 times in association with the fresh micropegmatite, 10 times with uralite and pegmatite, once only in an ophitic rock, 4 times only in glassy forms, and the remaining times is most often in dikes which elsewhere contain micropegmatite, or have the acid interstices plainly indicated by quartz, brown hornblende and mica, etc. It cannot be said that micropegmatite is an absolutely necessary feature of these interstices. It is merely the most unequivocal feature. The way the needles of apatite grow across these cavities does not suggest to my mind their origin from decomposed glass,† but suggests rather the apatite found in drusy or miarolitic cavities like those in the basalt of Capo di Bove.‡ In 13 out of 31 of the sections of the Lighthouse Point dike is apatite mentioned, but in not one of the marginal sections. In a number of other dikes the same thing is true. Ss. 757, 996, 997, 991, have it, Ss. 756, 994, 761, not, the latter three being marginal, and all the sections being from the same dike. This concentration in the center of the dike does not seem natural for a secondary origin.

If, then, these cavities were during the formation of the rock, at the close of the augite formation, filled neither with any of the previously formed minerals nor glass, they may have been filled with the residuum of the molten magma. Enough of the rock was formed to make it perfectly solid, for no farther motion could take place without disturbing the micropegmatite borders of the feldspar laths and fracturing the excessively delicate apatite needles. The remaining interstices seem, agreeing with the general law of increasing acidity in residual magmas, to have been filled with the final concentration of an acid aqueo-igneous magma which had been corroding the olivine and forming the less basic augite from it. In this magma were also concentrated the absorbed gases, aqueous and otherwise, which the dike margin originally contained and which, as the dike solidified at the margin, would probably be driven from it and concentrated at the center.

* Mik. Phys., II, 1896, p. 1117.

† Wadsworth, Minn. Geol. Sur., Bull. II, p. 68.

‡ See also Dana's Mineralogy: also Vogt, Neues Jahr-Buch für Min., (1894) i, p. 96, describes similar apatite needles in the cavities of slag.

The acid magma thus left seems to have proceeded to produce brown hornblende upon and out of the augite, brown mica upon and out of the iron oxides, as Smyth has suggested, and pegmatite growths on or out of the feldspar,* while apatite needles formed across the cavities. This explanation of these cavities accounts well (1) for their occurrence only at the center of dikes, (2) for the fact that the minerals formed and structures are those of more acid rocks, which we see in their obvious parallelism with the rocks more rich in micropegmatite, such as the diabase granophyrite, Ss. 11727 and 11831 (W).† The occurrence of quartz feldspar micropegmatite intergrowths is described by Rosenbusch within miarolitic spaces,‡ although in a private letter to Patton he expressed himself as not inclined to consider these granophyric growths as similar. Nor do I conceive that they were in cavities left after the consolidation of the whole rock magma, filled in by infiltrating foreign substance, though if they are truly secondary products, such cavities may have guided their deposit, but rather the refuge of that part of the magma that the loss of heat due to injection did not solidify. Thereafter the hot aqueous solution would, as we have said, react on minerals already formed, and would form crystals much more slowly, perhaps not until the solutions had been affected by percolation. They correspond thus to Brögger's§ second phase in the formation of his pegmatite dikes. The brown hornblende may be akin to barkevikite. Brown hornblende generally contains potash,¶ as we see from its abundance in alkaline rocks. It seems not impossible that the so called reaction rims around olivine and other miner-

*See foot note at end of § 9.

† Williams, *loc. cit.*, pp. 181, 182; Rosenbusch, Mik. Phys., 1896, II, p. 226; Patton in Ann. Rep. State Geol. Mich., 1891-92, p. 185.

‡ Mik. Phys., 1896, II, pp. 55, 67.

§ Groth's Zeitschrift für Kryst. 1890, XVI, p. 162.

¶ Cf. Dana's Mineralogy, 1892, pp. 396 and 403; Williams, Am. J. Sci. (May, 1890) XXXIX, p. 352.

als* may also be produced with the co-operation of residual magma. The minerals produced are often such as might be expected from such action, and like those we have in the acid interstices. It must not be forgotten that a theory of the origin of these interstices must account for the chemical character of the minerals formed in and about them, for the potash and for the chlorine and fluorine of the apatite and brown mica. Moreover, it is *a priori* almost necessary to believe that in rocks consolidating under such circumstances as to prevent the escape of aqueous or other gases there will be a residuum which cooling will have only a slight tendency to solidify. The fact that these interstices seem at times to be centers of decomposition is in full harmony with a conception of them as microdrusic.

Precisely the same phenomena as those we have been describing have been observed by Lawson about Rainy Lake,† the pegmatite and quartz being confined to the center of the dikes and associated with apatite. Analyses show that the silica and alkalies distinctly increase towards the center ‡ As may be inferred from what we have said, these dikes with acid interstices have well-defined fine grained, glassy and porphyritic walls. Ophitic augite rarely occurs in the same dike with micropegmatite, although it seems, comparing Lawson's description of S. II from the Stop Island dike with S. 11615 (W) from the Lighthouse Point dike, and S. 997 from the Brook sections, as though in some cases, between the glassy margin and the center with acid interstices, a zone occurs from 4 to 10 feet from the contact, where there are traces of ophitic texture.

In the marginal sections from these dikes (Ss. 566, 949, 875, 933, 962, 11762, 11616 (W) of the Lighthouse Point dike) the LABRADORITE, remaining essentially the same in character of extinction angles, etc., becomes much more variable in size, being as it were porphyritic, yet without any sharp line between the larger and smaller laths. Enclosures of glass and iron oxides, marginal or arranged parallel to (010), become much better developed than in the coarser grained rocks. These enclosures are sometimes tubular. The way in which the enclosures parallel to the lateral pinacoid are formed is well illustrated by cases in which the feldspar runs out into split and forked laths characteristic of rapid cooling (S. 11751). It often gathers into stellate radiate groups, in making which the Baveno cruciform twins are prominent (S. 11484). The already mentioned occurrence of younger sheaves of andesite feldspar

* See Kemp Bull. Geol. Soc. Am., 1893, V, p. 218, etc., also H. B. Patton in Ann. Report, State Geol. Mich., 1891-92, p. 19.

† Proc. Am. A. A. S. xxxviii, 1889, p. 246; Am. Geol., VII, 1891, p. 153.

‡ Compare the table of analyses at the end of § 11.

in the interstices of the ordinary intersertal, i. e., diabasic or tholeyitic, texture, is rare (Ss. 11811, 11807).

The AUGITE also tends to occur in the spherulitic groups already described. When finer grained, it also occurs in rounded or idiomorphic granules which do not fit closely to the feldspar. The olivine is in sharp idiomorphic forms (Cf. Fig. 23 and S. 11751), i. e. k (021) and b (010), and the cleavage face (100). It is generally bordered with granules of iron oxides, probably due to incipient alteration, or possibly magmatic absorption.

The iron oxides of the ground mass, MAGNETITE, are in those club shaped forms of growth that commonly occur where there is a little glass left, and are figured and described by Geikie* as characteristic of margins of dolerite. It is true in our rocks also that such forms are characteristically marginal. In S. 914 occur some brownish translucent branching forms, apparently ilmenite. In S. 11878 is a deep brown glass with eutaxitic growth forms.

The distribution of these rocks which contain the acid interstices confirms our conception of their character. They are characteristically dike rocks and occur in all the formations up into the Upper Huronian, being scattered through the great band of greywackes and slates that run south from L'Anse, and in fact everywhere except in the Keweenaw and younger formations. Now why are rocks of this type absent in the Keweenaw formation? Micropegmatite occurs only in pebbles in conglomerates. From Isle Royale we have, as we have shown, a continuous section of some 9,000 feet, represented by over 1,000 thin sections showing rocks of very similar, we may say almost identical chemical composition (compare the analyses of rocks in chapter IX with those of the end of this chapter), of various degrees of coarseness, and in all stages of surface decomposition. The acid interstices cannot therefore be wholly dependent on chemical character or coarseness, for we find all degrees of basicity of feldspar associated with great range in coarseness and freshness among the Keweenawan rocks, nor on the secondary alterations such as have affected the Keweenawan rocks, nor, as we have seen, on the dynamometamorphic alterations which have produced the amphibolites. We seem driven to the conclusion to which we came from internal evidence,—that the acid interstices are essentially dependent upon some condition characteristic of an intrusive mass. It may be a secondary alteration perhaps, *if of a kind which does not occur in flows*. Solution of a siliceous country rock, or intermixture with an

*Trans. Roy. Soc. Edin. xxix, Pl. xii, fig. 12, and p. 497. Cf. Rosenbusch, Mik. Phys., I, 1892, Pl. II, fig. 5, and II, 1896, p. 1012.

acid magma as described by Winge and Moberg * will hardly cover the case of a whole family of dikes, though it may be noticed that the kind of effect produced by solution of quartzite and granite by a basic magma would be expected to be analogous to that produced by an acid residual magma. This being granted, the difference in structure and grain are no argument against the conclusion supported by stratigraphic relations, that the quartz diabases are coeval with some of the Keweenawan traps, and are really their intrusive equivalents.† The orthoclase gabbro and diabases of Irving have points of similarity with this group, but much less acid feldspar.

We find indeed in the Keweenawan effusive rocks of similarly coarse grain interstices corresponding to the acid interstices, but filled with delessite, calcite like that which Törnebohm described as primary, chalcedony, etc. The formation and filling of these cavities may be explained as follows: The lava flow solidified first near the surface, and the basic feldspar forming (as in Fouqué and Lévy's experiments) before the augite, made a sort of trellis-work through the whole mass, which is thus rigid. Then the augite, the last to form, when it contracted in crystallizing, left interstices not in this case filled with residual magma, but with gas, giving the rock a porous yet not amygdaloidal texture, as these cavities do not have rounded walls.

They are of course filled at the first approach to alteration, generally first with a coating of delessite, whose fibers are at right angles to the walls of the cavities. They may be filled in by percolation in various ways Such an effusive texture is illustrated in Pl. VI, fig. 3, while the acid interstices are shown in Pl. XVI.

In prosecuting these investigations it was of course important to follow one dike from margin to center, just as Lawson had done,‡ and the results of this study on the grain of the Lighthouse Point dike and one other, are given in the table below. This table contains, beside the data as to grain, measurements of the extinctions of the feldspar, and also, for comparison, similar data from Lawson's paper, from Fouqué and Lévy's work on artificial rocks and from one of the large Keweenaw flows. In Chapter V more data will be found and Figs. 17 and 15 give graphic representations.

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*Rosenbusch. Mik. Phys., II, 1896, p. 1304, 1307; compare also Bayley U. S. G. S., Bull. 109, pp. 109–111, and Harker on the Carrock Fell gabbro, Q. J. G. S., 51, 1895, p. 125.

† All the similar rocks described by Rosenbusch, II. 1896, pp. 958, 1144–47, are also intrusive.

‡ Am. Geol., VII, 1891, p. 153.

DESCRIPTION OF PLATE XVI.

Illustrates the acid interstices and micropegmatite; the shading of the feldspar also indicates the varying direction of extinction dependent on the acidity. Compare this plate with Plate VI, Fig. iii; 35 diameters enlargement.

MICROPEGMATITE AND ACID INTERSTICES (S. 7931).

The curves of grain of Fig. 17 indicate, e. g., for the dike of Sp. 11426 (see § 5) a central zone of uniform grain for augite about 2-3 the total breadth; for the dike of Sp. 13749 a central zone of uniform grain for augite about 60% of the total breadth, and Lawson's statements are in harmony, indicating a similar zone less than 80%. If now we use Pl. IV to find to what elevation the curve numbered 8, which represents the temperature 2-3 the way from center to margin, continues to have practically the same slope as curves for points nearer the center, we find it is somewhat above 30, the initial temperature being 78.5.

Thus if we assume the constant temperature of the margin of the dike to have been 100° C. and the temperature of solidification and augite formation, after Barus (U. S. G. S., Bull. 103, p. 54) to be between 1095° C. and 1170° C., we shall have for the initial temperature of the dike, $(78.5 \div 30) \times (1170 - 100) + 100 = 2900°$ C. as a maximum, while if we assume, owing to the presence of water, a lower temperature of formation for augite, it would not be difficult to suppose as low an initial temperature as 1500° C.

Explanation of table:

In the first column is the number of the section, in the next six columns are notes on the composition, viz., in the second column the presence of micropegmatite noted by p, of quartz by q; in the third column the presence of biotite by b; in the fourth, the presence of brown hornblende by h, or of uralite by u; in the fifth, the presence of apatite by a; in the sixth, the presence of glass by g; in the seventh, the presence of eutaxitic growths of iron oxide by e; in the eighth, distance from the margin; in the ninth, characteristic feldspar extinction angles and miscellaneous notes; in the tenth, average length of feldspar laths, in millimeters; in the eleventh, average breadth of same; in the remaining columns, average linear dimensions of augite, magnetite and olivine, respectively, all the dimensions being determined in the case of my observations by measuring the dimensions of the largest individual in three different fields of view.

No. of specimen.	Micropegmatite, resp. quartz.	Biotite.	Brown hornbl'de, resp. uralite.	Apatite.	Glass.	Eutaxitic iron oxide.	Distance from margin.	Feldspar extinction angles, etc.	Feldspar.		Augite.	Magne-tite.	Olivine.	
Lighthouse Point dike. Fresh, coarse, central type.								To this group belong 11617 (W), 11622, 11636, 11666.	Average dimensions of constituents in mm.					
									1.65 x 0.34		1.29	0.7	----	Average of meas-urements for groups below.
869	p	b	h	a	----	----	12 ft.?	32°-30°	1.8	0.5	1.8	1.1	----	869
11763	p	b	----	a	----	----	?	23°-24°	1.6	0.4	1.3	0.9	0.5	11763
909	p	b	h	a	----	----	24 ft.	----	1.3	0.3	1.3	0.7	0.5	909
871	?p	----	----	a	----	----	12	----	1.8	0.5	0 9	0.6	0.5	871
947	p	----	----	a	----	----	30	----	1.8	0.4	1.1	0.5	----	947
965	?	b	----	a	----	----	39	----	1.7	0.3	1.4	0.5	0.6	965
934	p	----	----	----	----	----	23	{38°-32° {38°	1.5	0.3	1.0	0.5	----	934
941	p	----	----	----	----	----	24	{11°-11° {12°-12°, i. e. ab 60% An	1.7	0.3	1 0	0.6	----	941
Fresh; intermediate in grain. Compare 11708 (W) from another dike.														
									1.2	0.25	0.35	0.16	----	Average.
8148	?	b	h	a	----	----	----	----	1.2	0.3	0.6	0.3	----	8148
966	?	----	----	----	----	----	3 in.	----	1.2	0.2	0.1	0.3	----	966
Fresh; marginal. Compare 11719 (W) from another dike, also 11621 (W).														
									0.8	0.14	0.10	0.03	----	Average.
875	----	----	----	----	g	e	----	17°-17° 37°-35°, 24°-28°	0.8	0.16	0.40	0.1	----	875
933	----	----	----	----	?	----	----	----	0.8	0.16	0.16	0.02	0.2	933
949	----	----	----	----	g	e	----	30°-32°	0 66	0.2	0.16	----	----	949
962	----	----	----	----	g	e	----	----	0.75	0.1	0 06	0.02	----	962
11762	----	----	----	----	g	e	----	----	0.9	0.11	0.06	dust	0.2	11762
Thin section shows contact.														
13030	----	----	----	----	?	----	----	----	0 5	0.11	dust	dust	0.15	13030
Coarse; more or less altered. Compare 11675, 11672, 11615 (W). Williams gives the average dimensions of the feldspars as								{from	1.5	0.25				
								{to	1.	0.15				

Quartz diabase dike from cut on Iron Range and Huron Bay R. R.; 1500 paces N., 50 paces W. of the S. E. corner of S. 35, T. 50, R. 31.														
13749	----	----	----	----	----	----	20 ft.	----	1.9	0.8	1.5	1.00	----	13749
13748	----	----	----	----	----	----	8	----	1.7	0.5	0 8	0.80	----	13748
13747	----	----	----	----	----	----	21	----	1.2	0.2	0.7	0.40	----	17747
13746	----	----	----	----	----	----	0.5	----	1.0	0.16	0.2	0.06	0.3	13746
13745	----	----	----	----	----	----	0.0	----	1.2	0.16	0.1	0.002	----	13745
Lawson's Stop Island dike, Am. Geol., 1871, VII, pp. 153-164.														
IV	q	----	h	a	----	----	75	Analyses at end of chapter. Size of quartz 0.84	2.00		1.00	0.70	----	IV
III	q	----	----	----	----	----	15	Size of quartz 0.056	0.35	0.10	2.00	0.70	----	III
II	----	----	h	----	----	----	4	----	0.56	0.056	0.84	0.126	----	II
I	----	----	----	----	----	----	0	----	0.052	0.004	0.03	0.0147	----	1

Artificial rocks of Fouqué and Lévy. (Synthése des Min., etc., 1882, pp. 48, 60-75.)	Feldspar.		Augite.		Magne-tite.	Olivine.
Andesite; composed of 4 parts oligoclase, 1 part augite, kept 3 days at heat 3, i. e. low white heat (steel softens, copper melts, about fusion temperature of labradorite), gives	0.25 x 0.015		0.06 x 0.02			
Labradorite porphyrite; 3 parts labradorite, 1 part augite, kept 3 days at heat 3	0.25	0.025	0.05	0.025	0.01	
Basalt and melaphyre; 6 parts labradorite, 2 parts augite, 6 parts olivine; 48 hours at heat 2 (steel melts), cooled, then 48 at heat 4 (cherry red); porphyritic	0.15	0.03	0.05	0.015	0.005	
Ophites (a); 1 part anorthite, 2 parts augite, 4 days at heat 2, 3, days each at 3 and 4						
(b) 1 part anorthite, 1 part augite, 4 days at heat 2, 3 days each at 3 and 4, ophitic	0.4		0.75	0.04	0.015	
(c) 1 part labradorite, 1 part augite, only partly ophitic						

The Greenstone.

No. of section.	feet from bottom of flow.	Extinction angles of the feldspar.	Feldspar.		Augite.	Magne-tite.	Olivine.
15252	119	{38° 34°-24°; {23° 31°-23°; {7°-2° 39°-34°; {41° 19°-19½°; {37° 30°-28°	0.56	0.094	9 to 6	0.15	0.25
15253	95	14°-14°; 28°-30°; 24°-36°; 35°-37°; big phenocryst 43°-43°	0.46	0.13	7±	0.024	0.28
15254	73	{9°-4° 25°-27°}	0.30	0.07	5	0.11	0.33
15255	52	20°-23½°	0.39	0.06	4+	----	0.30
15256	24	----	0.38	0.04	2.9	0.12	0.17
15257	1	----	0.19	0.03	1.25	0.08	
15258?	0	----	0.27	0.04			

From these tables we see: (1) That the feldspar is very much coarser in proportion to the other ingredients, in the dike than in the much thicker flow, increasing in size toward the center, but increasing more rapidly in breadth than in length. (2) In both dikes and flows the augite and magnetite are but dust or very fine granules at the margin where solidification took place immediately after intrusion, while the olivine and the feldspar even at the very margin have a notable size and evidently began to form before the final arrival of the rock at its place of rest. This is expressed in diagrams by the fact that the curves of size for augite and magnetite begin at the margin at the origin of coördinates, while the others do not. The margin of a dike and the underside of a thick flow have just the same microlitic and porphyritic texture, and in both the feldspar has a porphyritic appearance, since beside the feldspar microlites that had begun to form before cessation of motion, there are smaller forked or skeletal feldspar microlites produced in the act of solidification. As we pass from the margin, however, the distinction of the two generations fades entirely away. In reality there never were two distinct periods of feldspar formation, but as the feldspar was forming, the chill from the contact intervened so as to suddenly wind up the process with a whole crop of little crystals. Toward the center the process continued with no intermission, and no marked break, as the change in the rate of cooling was less marked. (3) The grain of the augite is more uniform in the central part for the dikes than for the effusive. This indicates, as above said, that they were injected at a temperature considerably above that of the formation of augite. Suggestions that similar facts are generally true, i. e., the central part of the dike uniform in grain, and the margin for a narrow zone decreasing to aphanitic texture, occur in other authors.*

I wish to emphasize the fact that the feldspar began forming before the augite or magnetite, because in spite of the clear evidence of experiment contrary statements are often encountered. In the dike the formation of the feldspar seems to have continued without sharp interruption throughout the formation of the rock (though, as shown by the gradually changing extinction angles, it contains a gradually increasing percentage of Na_2O) and thus overlaps the formation of the augite at both ends. In the flow, on the other hand, the formation of the feldspar was sooner stopped and it is sharply automorphic.

*Lawson, Am. Geol., VII, 1891, p. 154; Bull. Denison University, II, 1887, 2, p. 134.

§ 7. Alteration forms of quartz diabase.

(a) Atmospheric. As we have said, the direct action of the atmosphere produces a narrow brown zone in which the augite weathers to iron hydrates and from the surface of which the diabasic arrangement of the feldspars and the granules of the magnetite project.

Another form of alteration, somewhat deeper seated, has been very carefully studied by Mr. Patton, and is given in the following descriptions. I will only add that this alteration is described by Van Hise* and by Rominger†, and has been already briefly referred to by Patton in the 1892 report, etc.

(b) Kaolitic alteration of diabase. (H. B Patton.)

S. 13456.

Diabase.

Cleveland Mine, Lake Shaft. Sec. 20, T. 47, R. 27.

Hand specimen. Rather fine grained; massive; dark gray; but weathers brownish. Fracture uneven.

U. M. Under the microscope the two principal ingredients, plagioclase and augite, are about equally abundant. The former is quite fresh, has well formed lath shape, and shows frequently a symmetrical extinction angle of about 30°; it is, therefore, labradorite.

The augite shows rarely crystal faces. Its color is reddish yellow. It is not as fresh as the labradorite, but contains more or less unrecognizable clouded substance of a greenish color.

Accessory; iron ore abundant as usual, and a little apatite.

A few small patches of vivid, dark green color, occur. These appear to be scaly in structure and to have not very high double refraction.

A chemical analysis of this rock made by Mr. Fred F. Sharpless is given at the end of the chapter.

S. 13457.

Chlorite schist. (Patton.) Cleveland Mine, Lake Shaft. Sec. 20, T. 47, R. 27.

Dike, cutting ore.

H. Sp. Has a crushed, schistose appearance; color dark gray, stained red with iron oxide on the surface. Feels greasy and has earthy smell.

U. M. Consists principally of a crushed, schistose, dark green, chloritic mass, throughout which are thickly scattered dark red hematite scales and powder.

Numerous colorless or light green patches are composed of minutely crushed feldspar, or probably of quartz. That some of this is feldspar is indicated by an occasional grain large enough to give a biaxial image in convergent polarized light.

This rock is very likely an altered diabase.

* U. S. G. S., Mon. XIX, pp. 357 to 358.
† Geol. Sur. Mich. V, Pt. I, p. 38.

S. 13458.

Diabase altered to ferruginous kaolin. (Patton.)

Cleveland Mine, Lake Shaft. Sec. 20, T. 47, R. 27.

H. Sp. Dull greyish red rock, soft and greasy to the feel, and with strong earthy smell.

U. M. shows the diabasic structure as No. 13456. The feldspar laths, however, have been altered into a white earthy substance, so fine grained as to appear almost isotropic; the augite is altered into a dirty brown, colorless opaque earthy aggregate. This substance is partly white, partly black ore dust and largely brown hematite.

The original magnetite grains appear to have remained unaltered and in addition there have been formed a very few small grains of quartz.

That the main mass of this rock is kaolin, is to be seen by comparing with No. 13459.

No. 13459.

Diabase altered to kaolin.

Cleveland Mine, Lake Shaft. Sec. 20, T. 47, R. 27.

H. Sp. Fine grained; soft and earthy; color very light gray, almost white. When scratched the streak is reddish, due to the presence of small particles of red oxide of iron, which, when thus crushed, is spread on a greater surface. The rock has a slightly greasy feel, a strong earthy smell, and adheres strongly to the tongue.

U. M. The original diabase structure is even here still plainly preserved, but both feldspar and augite have been altered into an excessively fine powder like that in No. 13458, but which contains a smaller amount of discoloring iron oxide dust, and with which occur very small angular grains of quartz that form perhaps one-tenth of the whole mass.

Although the hand specimen is so light colored, there are still left apparently all the original grains of magnetite unaltered. These on account of the contrast in color appear to form much more of the bulk of the rock than is really the case.

Preliminary experiments were performed first with the blowpipe, afterwards by means of microchemical reactions with hydrofluoric acid, for the purpose of determining the nature of this white powder.

B. B. It is infusible, gives off water and becomes blue when ignited with cobaltic nitrate.

These tests which indicate the presence of alumina and water agree with those for kaolin, and were confirmed by the microchemical reactions. These latter gave no trace of potash, magnesia or soda, but showed the presence of silica and alumina.

If any doubt could exist as to this being kaolin, it is removed by the chemical analysis of the whole material of the rock made by Fred F. Sharpless of the Michigan Mining School.*

*Below, p. 250.

In the analysis the amount of silica is, of course, augmented by the presence of free quartz. Of the iron oxides present all the FeO, 0.22%, and a proportionate amount of the Fe_2O_3, namely, 0.49%, is in the form of magnetite, which forms, therefore, 0.71% of the whole. As most analyses of kaolin show about 3% of Fe_2O_3, which, as in this case, is probably due to the présence of limonite, it is hardly worth while to consider separately the amount of this mineral. The remaining Fe_2O_3, therefore, namely, 2.07% will be thrown in with the kaolin.

To estimate what the relative amounts of kaolin and of quartz are, the average composition of kaolin was taken from Dana's Mineralogy and is given below.

Average composition of 10 analyses of kaolin			
	SiO_2	47.60	
	Al_2O_3	35.75	38.80
	Fe_2O_3	3.05	
	H_2O	13.20	

This gives us the ratio between the sesquioxides, silica and water to be 38.80 : 47.60 : 13.20. Now as all the sesquioxides in this rock may be assumed to belong to kaolin, namely 30.73 % (28.66+2.07) the relative percentages of SiO_2 and H_2O required for the kaolin may be found by means of the above ratio; for instance,

$$R_2O_3 \text{ (Dana)} : R_2O_3 \text{ (found)} = SiO_2 \text{ (Dana)} : SiO_2 \text{ (required)}$$

$$38.80 : 30.73 = 47.60 : 37.50$$

Similarly for H_2O

$$38.80 : 30.73 = 13.20 : 10.43$$

hence we have

30.73	R_2O_3
37.50	SiO_2
10.43	H_2O
78.66%	kaolin

This represents the proportion of kaolin present in the rock under consideration. The remainder consists of about 1% magnetite and impurities and about 20% quartz.

In the above reckoning it is noticeable that the estimated amount of water, 10.43%, very closely agrees with that actually found, 10.50%, which may be taken as additional evidence that the white mineral is kaolin.

The chemical change which this diabase has undergone may best be seen by comparing the above analysis, which is here repeated, with that of the comparatively fresh rock, No. 13456.

From this table one might infer that there has been considerable gain in silica, alumina and water, and a loss of all other ingredients, but with the attainable data it is impossible to prove that the gain in part of the

	I. No. 13456. Unaltered rock.	II. No. 13459. Altered rock.	III. Material apparently lost.	IV. Material apparently taken up.	V. Apparent percentage of gain.
SiO_2	47.99	58.22	....	10.23	21.32
Al_2O_3	16.57	28.66	....	12.09	72.90
Fe_2O_3	6.01	2.56	3.45		
FeO	5.13	0.22	4.91		
TiO_2	2.71	....	2.71		
MnO	trace				
CaO	9.36	0.17	9.19		
MgO	6.01	....	6.01		
K_2O	1.39	....	1.39		
Na_2O	2.00	....	2.00		
H_2O	2.64	10.52	....	7.88	298.48
Total	99.81	100.35			

substances is a real one, with the exception, perhaps, of water. In this latter case the gain is too large to be explained away, and, further, an increase of water over that in the original rock is imperative for the formation of kaolin.

If it were possible to prove that any one of the important ingredients had remained constant, or if it could be shown how great had been their loss or gain, it would be an easy task to figure out the actual loss or gain for all the other ingredients. In the absence of any such proof we may assume that a loss of silica is more probable than a gain, inasmuch as the alkalies and probably some other substances went off in the form of silicates. Further, if there has been an actual increase in the amount of silica there must have been a corresponding increase of Al_2O_3. This is highly improbable on account of the difficult solubility of this substance? On the other hand it is to be expected that this most stable of all the compounds present in the original would be affected least in the process of alteration.

Let us assume, therefore, that the Al_2O_3 has remained constant.* It appears from column V in the above table that there has been an apparent gain in Al_2O_3 of 72.90% while the H_2O has increased 298.48%, but SiO_2 only 21.32%. The apparent increase in SiO_2 is less than one-third that of Al_2O_3, i. e., if Al_2O_3 has remained constant, as is probable, then there has been an actual loss of SiO_2. In other words, although the

* As do Merrill and Smyth, Bull. Geol. Soc. Am., volumes VI, VII and IX [Lane].

product of decomposition is much more acid than is the fresh rock, this acidity is gained by the loss of the basic elements and not by the increase of SiO_2.*

(c) Uralitic alteration.

In the common alteration of the rocks of this group I have not happened to observe any shearing action such as Williams found in one of his slides, S. 11616 (W).

Almost the first thing to change is the olivine. In none of the sections is this absolutely fresh. The margin and cracks became lined with secreted iron oxide granules, and little green fibres. These little green fibres wander off into cracks in the feldspar, and into the acid interstices. They may gradually increase until they replace the olivine entirely. They are pleochroic and have an optically positive elongation while non-pleochroic sections show a negative uniaxial image. The birefraction seems to mount about to 0.019 (S. 965) or to 0.017 (S. 909) as a maximum in the strongly pleochroic sections. This substance has undoubtedly been called serpentine, but careful study shows that it is rather foliated, that it has transition forms to brown mica, from which, or rather from green mica it differs only in the strength of its birefraction, or in other words that it is intermediate between biotite and chlorite. When it replaces the olivine it is sometimes uniform in orientation (See Fig. 29, which may be compared with Fig. 23).

Something like what we have described has been also mentioned by Brauns† and called villarsite. Since, however, that is a transference of an old name to a new sense, a doubtful proceeding, and we do not really know the composition of the mineral that we are dealing with, and inasmuch as it seems to me to belong in all probability to the morphotropic series of mica-serpentine-chlorite,‡ standing intermediate between them in optical properties, it seems to me that mica-serpentine or green mica will suffice for a name.

* It will be noted that the analyses of the fresh rock and the conclusions of Van Hise and Patton, worked independently and on different occurrences, are almost identical [Lane].

† Zeit. d. Deutsch. Geol. Ges., 1888, Vol. XI, p. 467.

‡ According to Clarke's investigations of the compositions of the silicates, Am. J. Sci., XLIII, (1892), p. 190; Bull. U. S. G. S., No. 125, olivine and serpentine, mica and chlorite have a close analogy in chemical construction, all being formed out of $R_{12}(SiO_4)_6$ with R in olivine Mg_{12}; with R in serpentine in part

Mg—
|
Mg— , in part H-O-Mg—,
in part H—;

with R in chlorite made up of the same molecules as in serpentine and also the radical

H—O—
H—O— Al—

while in biotite in addition to the above bases we have an alkali radical containing (K — O — Al =) or something similar.

This change to green mica is not the only one that the olivine undergoes, although it always seems to be the first step after the secretion of iron oxides. In the center of the olivine pseudomorphs we have at times a colorless mineral of strong birefraction that I take to be talc. Carbonates also occur, and sometimes the olivine in alteration becomes pleochroic, yellow to reddish brown (Ss. 869, 941), apparently what has been called iddingsite.* This form of alteration seems to be more common, however, in the Keweenawan flows.

The beginning of the alteration of the augite is a fine lamellation or striation, parallel to the basis if it is changing to chlorite (Ss. 9290, 11735) or to the vertical axis if it is changing to uralite. The alteration spreads particularly from the olivine grains. Soon the change to uralite is fairly under way. At one stage the altered augite becomes almost opaque (S. 917), brownish, and fibrous (S. 906). Then working in from the margin it becomes greener (S. 936) and more clearly uralitic hornblende. At the same time the uralite encroaches on the feldspar (S. 917) and shows more distinct polarization colors. The color of the uralite near the feldspar has a more greenish or bluish green tinge (more alkali ?) while near iron oxides the color becomes more brownish (more iron ?) (Ss. 917, 991, 757). In the process of alteration occur grains of a yellowish epidote (S. 761), whose elongation appears invariably negative, i. e , it is probably flattened parallel to (100), and also twinned parallel to this face. The faces (001) and (101) also occur. Folia of brown mica occur (Ss. 11875, 937) at the margin or in adjacent interstices.

The first sign of alteration in the feldspar is generally its invasion along cracks by little folia, which at times exactly resemble the green mica that is produced from the alteration of the olivine, at other times seem like ordinary chlorite, and at other times (S. 880) pass distinctly into brown mica. Another type of alteration is shown in the occurrence of semi-globular brown micaceous patches (S. 11801). When the feldspar is very largely replaced (Ss. 907, 1071) the chloritic character of the replacing mineral is unmistakable, and with this chlorite is also associated an epidote, not so yellow as that which occurs in the chlorite that replaces augite, but more like zoisite in optical properties.

The iron oxides occur in two forms in the altered rocks. The large original grains of intergrown magnetite and ilmenite turn to the white opaque substance known as leucoxene. This change apparently begins

* Lawson, Bull. U. Cal., Geol. Dep., I, p. 31.

with the ilmenite, and thus we have (S. 791) angular pseudomorphs of leucoxene striped with bands of iron oxide, a phenomenon often heretofore noted.*

Beside these, sprinkled all over the rock, especially in the uralite, are minute granules of leucoxene and iron oxides.

Pyrite also occurs occasionally, but I have seen nothing absolutely decisive as to its primary or secondary origin.

§ 8. Teschenitic diabase.

The younger dikes of the iron-bearing or Huronian formations belong, as we have said, with great uniformity to the quartz diabase family just described and its immediate kindred marginal forms. The diabase granophyrites and olivine diabases are but slight chemical modifications, of no geological moment, and apparently of comparatively rare occurrence. All the other basic igneous rocks that have not suffered uralitization are but rare exceptions. There are the peridotites and serpentines, and the rocks grouped under the name of lamprophyre may be akin but are excessively altered and are, I feel confident, dike forms of peridotite. Then there are one or two rocks whose field relations are somewhat suspicious, and seem to be Keweenawan in type, and may be from the drift, as S. 1846 from T. 42, R 31, an anorthite rock ; S. 10161, 430 paces N., 2000 paces W., Sec. 20, T. 43, R. 33. One peculiar type which I should expect to find rich in TiO_2 is S. 513, which we may provisionally call a teschenitic diabase. Its description is as follows:

S. 513. Teschenitic diabase.

(Diabase; Wright.)

Nineteen hundred eighty paces N., 1565 paces W., Sec. 6, T. 50, R. 30, at falls ten feet high.

Strike N. 70° W. Dip S. 70°.

H. Sp. Fine grained; massive; dark gray with the diabasic laths barely visible to the naked eye.

U. M. Shows abundant plagioclase laths with interstitial violet brownish augite, plates of hematite or ilmenite, considerable uniformly distributed idiomorphic brown mica. In addition there is much green substance of at least two kinds.

Accessory; apatite, carbonates, titanite.

The feldspar has the usual characters of diabase labradorite. It is much clouded, especially along cracks, etc., by little scales of the green substance

*Rosenbusch, Mik. Phys., I, Pl. XV., fig. 2; Wadsworth, Minn. Geol. Sur., Bull. II, p. 64.

that have the properties of sericite. Sometimes the sericitic matter is massed together in the interstices, in which case irregular aggregates of titanite (?) are enclosed. The interstices not filled with augite are, however, more commonly filled with a greenish substance of lower double refraction, in radiating (+) fibers.

The augite is rarely idiomorphic, but sometimes distinctly so. It is distinctly pleochroic, 𝔟 always more reddish, while the other axes of pleochroism probably do not coincide with the optical axes. In the direction of the crystallographic axis, 𝔞, the light transmitted is light green. The color of the other axis is much like that ∥ to 𝔟. The optical angle about 𝔠 is moderate. One axis is much more dispersed that the other, and other sections show that it is the axis nearly parallel to the prism with $r > \upsilon$ as shown in Fig. 28.

The brown mica is thoroughly compact and idiomorphic, apparently uniaxial. Apatite needles are abundant.

This rock in its tephritic augite, primary biotite, abundant apatite, and peculiar alteration, has stronger affinities with the teschenites, than with the kersantites. I would still keep it in the diabase group as a teschenitic diabase.

§ 9. Diabase granophyrite.

A few sections and specimens may be referred to this rare petrographical type, which is probably only an extreme facies of the quartz diabases, since Williams's section from the Lighthouse Point dike, S. 11675 (W), seems from his description to have belonged to this type. This agrees with Rominger's remark that the supposed westward continuation of the Lighthouse Point dike contains more red feldspar.* Indeed it would not require much imagination nor twisting of the strikes to make the big dike at the Holyoke adit, Sec. 2, T. 48, R. 47, which we take as the type of the diabase granophyrites, continuous with the Lighthouse Point dike.

Some of the quartz diabases mentioned by Rosenbusch, and the Vosges "gang-granophyres" with labradorite† are probably similar. The relation to Lawson's diabases from the north shore of Lake Superior is discussed above and in § 11. F. D. Adams has also encountered similar rocks in Canada. As we shall see in § 11 when we take up the chemical relations of the group, though these rocks are chemically much more

* Geol. Sur. Mich., IV, p. 147. To the kindness of Messrs. Sutton and Seaman I owe an opportunity of examining some sections from this locality, Sec. 16, T. 48, R. 25, near the Brewery, viz. Nos. 38194-6, 425 The augite, labradorite, micropegmatite, apatite, mica, etc., are as in 7931, and the micropegmatite is nearly or quite as abundant. There is much greater yellow staining and somewhat greater alteration of the augite. It should be said that the above gentlemen notice the micropegmatite mainly on top of the outcropping knob and take it to be secondary.

† Mik. Phys., 1896, II, pp. 1111, 1144, 649.

acid than normal basaltic rocks (see analysis No. VI, at the end of the chapter) and thus akin to the diorite porphyrites, in texture, mineral composition and geological occurrence they are an extreme form of the quartz diabases. Analysis VI shows much more iron and less alumina than the true intermediate rocks, as may be seen by comparing the analyses quoted in Zirkel's Lehrbuch der Petrographie, 1894, II, pp. 485, 503, 545, or the analyses of porphyrites given by Cross in his discussion of laccolitic rocks.*

The following specimen is like this group, and very much like the salite diorites† but finer grained (augite about 1 mm. in diameter.)

No. 6963 (5716).

Quartz diabase, or augite granophyrite.

(Altered diabase; Wright.)

Six hundred fifteen paces N., 1992 paces W., Sec. 8, T. 47, R. 45; from pit No. 7, 18 feet from surface.

U. M. Is a moderately coarse rock with long slender reddened laths of oligoclase, and about equally long and slender light colored but much altered pyroxene. There are also grains of magnetite, sometimes apatite.

Interstitial: much quartz, orthoclase often granophyric, secondary epidote, chlorite.

The feldspar is always reddish, even in the granophyric growths. It is in spots replaced by a positive chlorite of considerable birefraction.

The feldspar extinctions are moderate (19°–14° with 9° in an albite Karlsbad twin).

The forms are very sharp. The twinning lamellæ are not numerous.

The pyroxene is altered into hornblende and chlorite. Both alterations proceed along the basis, and where we have (100) twinning as very often happens, give a herring bone pattern (augite extinctions 41°–43°, 41°–48°). The augite is often in stellate groups and there is one group which is composed of two orthopinacoid twins at right angles which suggests a twinning after ($\bar{1}11$). The alteration is precisely that described by Törnebohm in the Konga diabase, and does not attack a brown marginal hornblende that occurs around the augite.

The quartz is in irregular grains with a granophyric border against the feldspar. When the micropegmatite shows, as often happens, rod shaped forms, these have ex. 0°. Most of the apatite, which has enclosures down the middle, lies in the micropegmatite.

The iron oxides are sometimes coated with leucoxene, and occur in large irregular grains, with indications of crystalline form.

The chlorite has essentially the same properties whether in the augite, the feldspar or, as happens to a limited extent, filling the interstices with an

* Fourteenth Annual Report, U. S. G. S., p. 227.

† See footnote at end of section.

irregular aggregate of fibers. It often borders the feldspar all around. When it enters the feldspar it willingly follows the twinning lines parallel to the elongation in marked contrast to its arrangement in augite.

This rock answers to the quartz, i. e., Konga diabase of Törnebohm most nearly in the idiomorphic augite with (100) twinning and decomposition, in the apatite and the magnetite, and the quartz and the granophyric growths. The only point of difference is that the pyroxene is here mostly light colored but it seems to me that the blanching may be a first step toward alteration. The brownish hornblende also occurs so irregularly at the margin of the feldspar that that might be secondary too. The rock must, however, be extremely acid for a diabase. Some of Irving's augite syenites are probably akin; it is weathered but not metamorphosed.

S. 14631, 455 paces N., 1325 paces W., Sec. 35, T. 49, R. 27, is probably of the same group; the augite is wholly changed to chlorite.

S. 7931.

Quartz diabase, granophyrite; Patton.

(Diabase; Wright).

Twelve hundred sixty paces N., 460 paces W., Sec. 2, T. 48, R. 27. Dike in ravine.

H. Sp. Medium grained; massive; very dark green, with reddish spots.

U. M. Shows the structure of a tholeyite, namely long lath shaped plagioclase, with mostly allotriomorphic grains of augite, iron ore, and a little brown biotite, and a well developed mesostasis. The mesostasis is here unusually abundant, occupying about one-third of the whole. It consists essentially of a beautifully granophyric intergrowth of quartz and feldspar (Pl. XVI) (probably orthoclase*), with which occurs here and there a grain or two of quartz, and a greenish, often radiated aggregate of a micaceous mineral having the pleochroism of chlorite. Very characteristic for these acid interstices are very long threadlike needles of apatite which pierce through granophyric aggregate and mica and often extend out into the main rock, cutting into or through feldspar and augite. Frequently half a dozen or more needles run parallel to each other, looking like scratches in the slide.

The feldspar of the granophyric interstices shows no twin striae. It is stained a deep reddish brown.

The feldspar (labradorite) is the only ingredient which possesses idiomorphic form. All others are irregular in shape except where they come directly in contact with the acid interstices.

The augite is of a light violet green color. It shows sometimes an alteration into brown hornblende. This seems to take place next to the acid interstices. More usually it shows an alteration into a slightly greenish substance which penetrates from the edges into the augite grain. Only in sections parallel to the clinopinacoid (010) does the substance appear to assume definite shape.

* Determination by Becke's test shows that, as is generally true in the micropegmatite, the greater index of the feldspar is less than the less index of the associated quartz, and so it must be either albite or orthoclase, and the K_2O in this specimen (analysis VI at the end of § 11) shows that it is the latter when we consider how much soda is required for the labradorite. [Lane.]

Here it has a fibrous appearance, the fibers being parallel with the basis of the augite. It shows an extinction angle of about 20° and has a double refraction about equal to that of hornblende. (The extinction is inclined 20° to the basis of the augite.)

The relative ages of the plagioclase and augite are uncertain, for the augite, though mostly of irregular shape, often encroaches to a slight extent upon the plagioclase.

This rock is an extreme form of the granophyric quartz diabases, but seems worthy of a special name.*

* Bayley's reference to quartz diabase, U. S. G. S., Mon. XXVIII, pp. 519-520, comes to hand while this volume is in press, just in time for notice. The occurrence which he takes as a type of quartz diabase, I had considered best described as an augite (salite) diorite and had not intended to include it in this group, although I had written "this rock resembles the uralite granophyrite" (see above, p. 255). "No. 6963 very markedly and hence is connected with the diabase granophyrites of which it may be an extreme form." Dr. Hubbard indeed was inclined to class it as a syenite, and on revision I am inclined to agree with him and a reference to augite syenite would not be unnatural. It is referred to by Brooks, Wis. Geol. Sur., 1879, III, p. 568, as related to the Picnic Point rocks near Marquette, which have been called porphyritic hornblende diorite, hornblendic syenite by Wichmann, porphyritic syenite by Rutley, diorite or amphibole granite by G. H. Williams (U. S. G. S., Bull. 62). As Bayley's map shows, its occurrence is in a small massif over one-quarter of a mile in diameter. It may be related to the normal quartz diabase somewhat as the melaphyre porphyrite is to the ophites, but in addition it is decidedly more like a deep-seated plutonic rock. Our section 13024 is considerably coarser grained than any of Bayley's (Nos. 16748, 16750, 16890), however. Bayley's sections are as fine for illustration of micropegmatite as I have seen, and they are remarkable for the exceeding fineness of the interdigitation of quartz and orthoclase which is at times almost submicroscopic, and finer than usual in the quartz diabases. I have also been permitted to see the sections of the Michigan College of Mines, Nos. 38300-38360, from this same knob.

The hand specimen shows blades of a dark augite, hard, but without the silky lustre of hornblende. These blades are up to 12 mm long, or more, and often about 10 mm. In nearly equal proportions a red feldspar is present, which is often in narrow striated laths, in lengths running 5, 4, 3, 3 mm, and but a mm. or so broad. Under the microscope we see long laths of acid oligoclase or orthoclase, which run out into marginal intergrowths with interstitial quartz. There is also chloritized green mica with well marked halos, ilmenite partly changed into leucoxene, and most remarkable of all very long crystals of colorless pyroxene much decomposed, but changing into a greenish brown mica and generally not into hornblende. The pyroxene seems to have had originally an hourglass form, with the outer layers most liable to attack and hence more changed into mica.

So far as the general question of the origin of micropegmatite is concerned, Bayley's sections, especially No. 16750, certainly show cases where the micropegmatite appears to replace the older feldspar, and I presume one inclined to that opinion would look at them as proofs of the secondary origin of the feldspar. And yet I cannot rid my mind of the conception that it is a magmatic action, that the older feldspar has been attacked and corroded in the fashion described by Michel Lévy. (Roches Éruptives, pp. 3, 4; Cf. Ros., 1896, II, pp. 216-230.) However, whether secondary or magmatic in origin, it is much easier chemically to conceive of a saturation of a potash feldspar by quartz in such way as to convert it to micropegmatite than of a labradorite, and in this Michigamme knob even the older feldspar which apparently has been corroded, and is replaced by micropegmatite, is largely orthoclase (not twinned, both indices of refraction much less than the lower index of quartz, appropriate extinctions, microcline structure occasionally visible but mainly in the younger fresh generation) or albite, $Ab_{19}An_1$ (about 5% An, Manebach twins very common, also pericline, Karlsbad and albite laws). The greater index of refraction is very close to the lower one of quartz, the lower index much less;

Extinctions	+4°	+9°	with 13°	+7°	Karlsbad
	8°	—16°	with	—12°	Karlsbad
	9°	—13	with 9°	—9°	Karlsbad
	9°	11°	with 16°	—5°	
	23°	—14°	with 10°	+17°	
	10°	—10°			
	8°	—4°)			

Hence in this knob one difficulty in the way of accepting the secondary origin of micropegmatite, viz., the rarity so far as reported of a secondary alteration which increases the percentage of potash (Cf. Merrill, Rocks, Rock Weathering and Soils, and C. H. Smyth, Bull. Geol. Soc. Am., IX, p. 257), is removed.

It should also be said that Bayley's sections are distinctly finer grained than mine. The feldspar does not occur in diabasic laths but in hypidiomorphic rectangular areas with occasional longer laths, as in granite. Similar may be the occurrences of micropegmatite cited in Ros. 1896, II, pp. 215, 219. If we assume all igneous rocks to be derived by liquefaction of a solid crust by relief of pressure, as I am inclined to think (Bull. Geol. Soc. Am. V, p. 269), the appearance of the micropegmatite could be explained as due to a relief of pressure leading to the corrosion of the earlier crystals, followed by speedy solidification of the partially liquefied rock as micropegmatite. But it is also conceivable that the potash which is leached out in ordinary weathering may be deposited in the shape of micropegmatite at greater depths. But unless these depths are very considerable I cannot understand why the micropegmatite is so confined to intrusive rocks as it seems to be.

Tabulated observations by Lane on dike of Holyoke adit.

No. of dike.	Composition and character of feldspar.	Extinction angles observed in twins.	Size of feldspar in mm.	Size of augite grains.	Size of magnetite.
7931	Ab_1An_1; moderate extinctions but lower than usual in quartz diabase.	{ 21° { 17°–21° { 14°–10° { 30° { 19°–14° { 9°	1 x 0.4		
7940	Small extinction angles.		0.40 x 0.1 0.3 0.03 0.6 0.1		
7954	Ab_2An_1 small extinction angle.	0° 0° 0°	av. 0.4 x 0.08 0.6 0.01 0.4 0.1 av. 0 25	0.3 x 0.2 near margin.	
7957	Ab_1An_1.	0° 15°–21°	1.3 x 0.2 1.0 x 0.3	0.7 x 0.3 0.5	near center
14604	Ab_2An_1; small extinction angles.	0°– 0° 0°–10° 0°–15° 2°– 4°	1 8 0.2 1.4 0.3 2.0 0.3 1.7 0.3	0.5 0.6 0.4 0.3 0.4 0.3 0.38	0.3 0.3 0.5 0.2 0.5 0.2 0.33

§ 10. Contact action of diabases.

The various diabases probably have the same contact action, regardless of the variety to which they belong. The considerable variety in the character of the contact zones seems due rather to the different character of the country rock or to the different physical conditions at the time of the formation of the contact zones. At any rate we have not noticed any connection between the character of the intrusive rock and the varying character of the contact.

(a) Production of touchstone or lydianstone.

Perhaps the most simple form of contact zone occurs in the slates, when the rock adjacent to the dike is simply indurated, so that the cleavage is destroyed, and is replaced by a conchoidal fracture, while the rock becomes much harder—in fact a regular touchstone, i. e., lydianstone or basanite. Such contacts are illustrated by specimens between Sp. 407 and Sp. 415, T. 48, R. 28, and between Sp. 382 and Sp. 392, about 225 paces N., 825 W., T. 49, R. 28 and by Sps. 10155, 10166, 10312, but is perhaps best studied in S. 9396, 920 paces N., 550 paces W., and S. 9397, 925 paces N., 555 paces W., Sec. 28, T. 51, R. 31, altered by the olivine diabase dike represented by S. 9398.*

The unaltered rock is represented by S. 9395, 1940 paces N., 1478 paces W., Sec. 23, T. 51, R. 31, from the slate quarry not far off. It is a common black slate, with

*Cf. Bull. Denison University, II, 1887, Pt. 2, p. 127.

no apparent grain, very slaty, yet the cleavage is not perfectly smooth. A joint plane is coated with pyrites. Under the microscope it shows a cryptocrystalline quartz-feldspar aggregate, with minute folia of mica, and chlorite, and is much clouded with irregular black carbonaceous dust. There are in it also recognizable grains of leucoxene and iron oxide and minute prisms of tourmaline such as characteristically occur in these slates, doubly terminated, 0 R (or ± ½ R) bluish; brown, R, antilogous.

Now Sp. 9396 has no apparent grain nor cleavage, but a flat conchoidal fracture, full of glistening points, which give it a more siliceous appearance, and it is indeed harder than 6, and is a genuine touchstone. Under the microscope we see that the rock appears very much clearer, and more like the secondary ground mosaic of a quartz porphyry. The mica folia appear fewer but better defined and the tourmaline somewhat scarcer. This last fact may not be connected with the contact zone, however.

The rock producing this alteration is an ophitic olivine diabase, with the olivine thoroughly altered. In this connection should be mentioned Sp. 9397, a graywacke, which is farther from the contact line but appears somewhat indurated and reddened as by igneous contact.

(b) Spilositic alteration. A somewhat different alteration is illustrated by Ss. 13776 to 13779 of Sec. 9, T. 51, R. 31, and also by S. 9323, about six feet from the contact with Sp. 9324 (a quartz diabase), 200 paces N., 1900 paces W., Sec. 22, T. 50, R. 33,—also by S. 9327, 300 paces N., 1420 paces W., Sec. 22, T. 50, R. 33, near which is Sp. 9326. Sp. 13323 is akin.*

S. 9323 is a coarsely fissile rock, dark gray, turning lighter brownish green, and under the microscope appearing to be a very fine grained chloritic rock, peppered over with iron oxides, showing some sericite and a quartz-feldspar background which extinguishes in flecks. There is also some leucoxene and not a little of the carbonates. The flecks appear due to a prevalence of green mica over chlorite and a somewhat coarser quartz-feldspar aggregate. Between the flecks the aggregate, through its self-compensating action, gives low polarization colors and the chlorite is of course almost isotropic. No trace of the flecked appearance can be seen without the nicols.

In S. 9327 the spilositic flecked texture is much more pronounced. Chlorite is absent and sericite or kaolin abundant in the flecks, and immediately about them is a darker zone of iron oxides and chlorite. The margins are clear and the center rusty with iron oxides. To the naked eye the round reddish flecks on a greyish green ground are plain and very abundant. The rock is highly fissile, soft, and has a strong earthy smell.

(c) Alteration of granite. Upon granite these diabases produce a reddening which is shown in Sp. 382 and Sp. 383A from Sec. 19, T. 49, R.

*See Geol. Sur. Mich., V, Pt. I, p. 66; Cf. Analyses D. and E., U. S. G. S., Bull. No. 148, p. 97.

28, but especially well by the following suite: Sp. 11801, a fresh quartz diabase dike, 40 paces N., 850 paces W., Sec. 3, T. 48, R. 25; Sp. 11802, a piece of the same, enclosing a small reddened fragment of the granite gneiss; Sp. 11804, a piece of reddened granite from the contact; Sp. 11806, a piece of a granite dike in the granite gneiss, which is itself altered in the same way.

To the naked eye the main feature is the reddening already mentioned, and the microscope does not show much more alteration. The descriptions of Ss. 11802 and 11804 will be sufficient. They are as follows:—

S. 11802.

Gneiss reddened by the visible contact of the marginal facies of a quartz diabase, No. 11801.

Thirty paces N., 850 paces W., Sec. 3, T. 48, R. 25. Contact of dike with granite on S. side. For a distance of from 2 to 4 feet on each side of the dike the granite is very red.

H. Sp. Shows a reddened granitic patch adjoining a very fine grained porphyritic blue-black trap like No. 11762.

U. M. Is composed of quartz, reddish discolored feldspar, brown mica, chlorite and carbonates.

Accessory: apatite.

Encircling about half the slide, as a rim, is a narrow zone of a basic rock with ferruginous base and sharply outlined little laths of plagioclase that have but two or three lamellæ. Immediately adjacent to this the grains of quartz interlock, are small and discolored with carbonates, but we pass immediately into larger, irregular grains of quartz, that show undulous extinction. The feldspar, at times plagioclase, is heavily clouded, especially at the margin, with orange-colored ferrites.

The apatite occurs but seldom, and then in fairly large grains. Chlorite, carbonates, etc., occur as rare accessories.

S. 11804.

Gneiss, reddened by contact.

Thirty paces N., 850 paces W., Sec. 3, T. 48, R. 25.

Granite in direct contact with dike.

H. Sp. Medium grained; massive; brick red.

U. M. Consists of reddish discolored feldspar (orthoclase and oligoclase?), quartz, and a little mica-chlorite or serpentine.

Accessory; iron oxide, zircon, apatite, carbonates.

The feldspar and quartz are not intimately mixed, but in separate although interlocking patches, the patches of quartz being rather rounded and from 2 to 3 mm. across.

The reddish discoloration is confined mainly to the margin of the feldspar. Otherwise the feldspar is fresh. There is one Karlsbad twin, and not frequently there occur very narrow and numerous lamellæ that show the albite law (indicating a soda-lime feldspar).

The quartz is almost free from the reddish discoloration, but it is full of lines of enclosures, mainly gas, or liquid with much gas. It also contains zircon and other irregular grains that have strong optical powers (a Ti-mineral?).

The lines of enclosures pass through different grains of the same quartz patch indifferently, but only occasionally pass through to another patch.

The small amount of interstitial green substance that occurs has a yellowish green color, positive fibers, and birefraction more than that of quartz. It is distinctly dichroic, with greater absorption parallel c, and acts like serpentine.

Apatite is not abundant, but when it does occur, it is in grains just visible to the naked eye.

Carbonates are mixed in with the serpentine.

(d) Adinoles (?).

Another less common alteration, not so certainly attributable to the diabase, consists in the production of cherty bands which are not black, but vary from white to flesh-colored tints. They are then indistinguishable to the naked eye from some of the jaspers of the iron-bearing rocks. Sp. 11868 seems to be a rock from this class, and appears to have been altered by the dike represented by Sp. 11865. The presence of a considerable quantity of feldspar brings it in the class of adinoles, and separates it from the jaspers and hornstones. It can be recognized only with difficulty by the microscope, being more certainly identified by tests for soda. Sp. 11828 may have been thus altered by Sp. 11827; its description is as follows:—

No. 11828.

Adinole or chert.

Eight hundred paces N., 875 paces W., Sec. 2, T. 47, R. 25.

Dolomite schist, impregnated with sulphuret of copper.

H. Sp. Is associated with a vein containing chalcocite and chalcopyrite; aphanitic; massive, but banded; brownish.

U. M. Is composed of minute grains (.02mm.) of quartz and feldspars on a fine grained micaceous ground full of grains of pyrite.

Accessory: iron oxide, large folia of white mica.

The grains of quartz and feldspar are of irregular form and distribution, parts of the groundmass being apparently quite free from them. They are both quite clear and can be distinguished only in convergent light, or by the occasional appearance of albite lamellæ. Feldspars appear to predominate. The finer grained micaceous mass has a brownish hue and a parallel arrangement with abundant random scales. Now and then a large random leaflet of a much clearer mica occurs.

The iron oxide grains are irregular.

The pyrite is in irregular patches of brassy lustre and is very abundant.

This is apparently a sericite schist, but the hand specimen shows that it is an indurated chert (or adinole). The induration may not be due to the dike, however.

(e) Sillimanitic schist.

Another interesting rock which appears to be due to the contact action of the continuation of the Lighthouse Point dike is S. 963. This sillimanitic hornstone appears to be due to the influence of S. 962 on the hornblende schist, S. 964. The descriptions of the specimens are as follows: —

S. 962.

(Basalt melaphyre; Wadsworth. Diabase; Wright.)

Sec. 23, T. 48, R. 25.

South side of Michigan St. Contact of diorite schist on the north and diabase on the south.

H. Sp. Much finer grained at one side; massive; bluish black. (Breaks with a conchoidal fracture, weathers brownish, and shows porphyritically enclosed lath shaped feldspars. Wadsworth.)

U. M. Porphyritic greenish pseudomorphs of olivine and laths of labradorite may be seen. The latter grade into the laths of the ground, which contains in addition augite in granules and spherulitic sheaves, octahedra and rarely skeleta of magnetite, and probably a little glass.

Olivine in idiomorphic forms has been replaced by a greenish dichroic substance (apparently uniaxial, with strong double refraction, pleochroism, $\mathfrak{a}$, yellow, $\mathfrak{c}$ or $\mathfrak{b}$ green as in Fig. 29).

The labradorite laths are as in S. 949, and the augite has the same tendency, there noticed, to undulous extinction. The augite granules fit loosely together. This implies the presence of glass.

S. 963.

Hornstone.

(Schist, amphibole schist; Wadsworth. Diabase; Wright.)

Sec. 23, T. 48, R. 25. South side of Michigan St. Contact with diorite schist.

H. Sp. Aphanitic black slate; banded; indurated. There is a very harsh feel in grinding the rock. Some very hard mineral must be enclosed. This also points to sillimanite. (The specimen is produced as a contact alteration of the diabase, No. 965, with an amphibole schist. Wadsworth.)

U. M. Is a schistose rock with outlines of large porphyritic feldspar, and a greenish ground containing quartz, brown mica, etc. The whole slide is thickly strewn with minute prisms of (possibly corundum) sillimanite. The minute prisms of sillimanite cloud the feldspar beyond exact identification. In the feldspar they are all parallel (+ ex. 0°, yellowish color, strong refraction, but only moderate double refraction). They would be taken for epidote or zoisite if it were not for the uniformly + extinction. In those minerals it is generally negative. There is no other mineral, with the properties of this one, but sillimanite. Moreover, it does not seem soluble in HF. The green part of the ground is somewhat opaque, with a granular structure and nearly isotropic. On this greenish opaque ground are clear dots of quartz and black irregular dots of magnetite. I should think this a contact alteration of a porphyrite, which may have been previously dynamometamorphosed and I should look for contact action.

S. 964.

Hornblende schist.

(Schist, amphibole schist; Wadsworth. Diorite schist; Wright.)

Sec. 23, T. 48, R. 25, south side of Michigan street, 2 feet from contact with diabase, i. e., the comparatively unaltered rock.

H. Sp. Very fine grained; dense; dark greenish gray.

U. M. Is a uniform non-porphyritic rock, which contains very slender prisms of trichroic hornblende that interlace, with a general parallelism, on a fine grained quartz-feldspar mosaic. There are scattered grains of iron oxide, sometimes in nests with leucoxene.

Other accessories seem to be lacking. The hornblende varies somewhat in color; the larger slender prisms are quite dark bluish to deep green.

(f) Salite bands in hornblende schist?

Finally it is barely possible that such salitic bands as occur in hornblende schists and are illustrated by Sp. 492, may be due to the influence of diabases like Sp. 497. The description of S. 492 is as follows:—

No. 492.

Salitic hornblende schist.

(Diorite schist; Wright.)

Five hundred paces N., 125 paces W., Sec. 27, T. 50, R. 28. Strike N. 45° W. Dip vertical.

H. Sp. Very fine grained; slightly schistose, with lustrous foliation planes, a reddish feldspar vein, and a lighter greenish band in which the salite probably occurs.

U. M. Shows irregular prismatic grains of hornblende, abundant interlocking feldspar and much iron oxide and leucoxene in the form of a fine dust. In part of the slide the hornblende is replaced by a light green pyroxene (salite?).

Accessory; apatite, titanite in grains, epidote.

The hornblende is the common kind and occurs in prisms or in large patches which are in this slide all cut nearly at right angles to b (100) ($-2V = 75°$ and $\mathfrak{c} - \mathfrak{a} = .018$ to .028; + ex. = 18°). Sometimes it and the salite are in parallel intergrowths.

The salite has the higher birefraction, but not the peculiar tints due to dispersion that epidote has. The cleavage is well developed and the extinction angle large. It has a peculiar light greenish tone and is not perceptibly pleochroic. The refraction is high.

The interlocking feldspar is much altered, having small micaceous folia, and a reddish discoloration. Here and there granules of leucoxene and epidote occur.

Titanite occurs also in large, light, recognizable grains. Apatite occurs in small sharp grains at times imbedded in hornblende.

§ 11. Chemical relations.

If we study the table of analyses given below, we note how extremely alike * the first five analyses are, and in Bull. No. 148 of the U. S. G. S. many similar analyses may be found (N., p. 70; A., p. 90, rather more silica, as most of the triassic diabases have; E., p. 185; E., p. 190; L., p. 200; etc.). But the five chosen, though widely separated geographically, belong to very nearly the same epoch. We note again, comparing them with the table of analyses in Chapter IX, p. 215, taking the average of the analyses, that they so strongly resemble those analyses of flows, that I cannot see any characteristic difference.

The inverse relation of magnesia and alumina noted in all the analyses is probably due to imperfect separation, an analytical error.

We can see, too, comparing VI with Shutt's analyses, VII and VIII, that the diabase granophyrite stands in the same relation to the ordinary diabases as the center of the Lawson dikes to the margin. There is an increase of soda, potash and silica toward the center. This is all we can be sure of, considering the imperfect character of the analyses. Still it does not seem likely that the alumina increases with the alkalies as in Iddings's absarokite series (Am. Jour. Geol., 1895, III, p. 935). If we contrast the differentiation already studied in the flows in chapter IX we see that that also is of a different character, for there the lime and soda vary somewhat as they do here, but there is no equally important concomitant change in silica. In fact it requires some imagination to detect a concomitant change of silica at all. Moreover, the potash increases in the dikes as it does not appreciably in the flows. This difference in the chemical character of the differentiation corresponds to a mineralogical difference, for in the case of the flows it is principally a question of the relative abundance of augite and feldspar, whereas in the dikes free quartz and orthoclase occur. It is hardly safe to say whether

*With the exception of the alumina in Shutt's analyses which must be incorrect, including MgO, and perhaps iron, for there is nearly enough alumina to make the rock with the given proportion of CaO: Na_2O (Cf. Pl. V) all feldspar, whereas we know from the descriptions and figures that there is a large amount of augite and other less aluminous constituents. (Cf. Pirsson, Am. Jour. of Geol., 1896, IV, p. 689.)

the difference in attitude, pressure, temperature, or of aqueous vapor retained determines the difference in differentiation, though I should think that the latter factor might be especially important in affecting the distribution of silica. One might easily imagine that the force of gravity affected the separation and settling of the heavier augite in the flows, while in the dike the differentiation was due to the segregation toward the center of that part of the magma most soluble in a trifle of superheated water. One has only to watch the behavior of superheated solutions of sugar, in other words, candy syrups, to see how a very little water may serve as solvent for vastly more than its bulk of solid. The following extract from Dudley's presidential address to the American Chemical Society is suggestive.*

" * * in most modern steel works large ingots are now the rule, and in large ingots, which take considerable time to solidify from the molten condition, analyses show that some of the constituents of the steel are not uniformly disseminated throughout the mass. This separation of the constituents during cooling, technically known as 'segregation,' is characteristic of the carbon, the phosphorus and the sulphur. Furthermore the segregation appears to be worst in the upper third of the ingot,"—as in the upper part of Keweenawan sheets.

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.
SiO_2	47.99	47.90	47.83	47.50	46.94	54.11	57.50	52.47	58.22	41.60
TiO_2	2.71	0 82	....	....	....	0.85	....	....	....	3.79
Al_2O_3	16.57	15.60	†30.28	†22.44	16.91	12.09	†23.44	†25.54	28.66	†37.20
Fe_2O_3	6.01	3.69	4.57	7.40	12.53	4.00	5.07	6.31	2.56	3.21
FeO	5.13	8.41	....	....	4.16	11 51	....	....	0.22	0.30
MgO	6.01	8.11	4.32	3 71	8.20	3.47	2.76	2.31	....	0.02
CaO	9.36	9.99	6.72	10.21	9.00	6.72	5.62	6.62	0.17	0.23
Na_2O	2.00	2.05	1.30	1.62	2 15	2.73	2.01	3.23	....	0.07
K_2O	1.39	0.23	tr.	1.29	0 54	1.49	0.45	0.54		
H_2O	2.64	2.49	loss 2.05	loss 2.85	loss 0.26	1.39	loss 2 25	loss 1.28	10.50	13.83
P_2O_5	....	0.13	2.19	0.34	0.28	0.12	2.02	1.16	....	0.14
Sum	*99.90	100.15	99.26	97.36	*100.75	99.23	101.12	99.46	100.33	100.85
Sp. Wt.	....	....	3.028	2.927	....	....	2.856	2.870		

*Summation incorrect in original reference.

†Erroneous.

I. Sp. 13456, Lake Shaft, Cleveland Mine, Sec. 10, T. 47 N., R. 27 W.; analyst, Sharpless, Geol. Sur. Mich. Ann. Report 1891, p. 141; with MnO_2 tr.

II. Sp. 12880, Sec. 13, T. 47 N., R. 46 W., Mich.; Analyst, Chatard, Van Hise, U. S. G. S., Mon. XIX, p. 357, Bull. 148, p.103, with trace Cr_2O_3; 0.10 NiO (CoO); 0.17 MnO; 0.38 CO_2; 0.03 SO_3; 0.05 BaO; feldspar also analyzed = Ab_2An_3 (*loc.*

*Science, N. S. (Feb. 11, '98) No. 163, Vol. VII, p. 188.

cit., p. 352. I do not think it admissible to include in the feldspar the iron with alumina, and magnesia with lime.)

III. Stop Island dike near wall: F. J. Shutt, analyst; Lawson, Am. Geol., VII, 1891, p. 158. Lawson has some six more or less complete analyses of the same type as III and IV.

IV. White Fish Bay: analyst, Shutt, *loc. cit.*, p. 161; near contact.

V. Center of olivine bearing diabase, Skrainka; Missouri Geol. Sur., IX, Mine La Motte sheet, p. 38.

VI. Sp. 7931, diabase granophyrite; analyst, Sharpless, *loc. cit.* 1891, p. 134, with MnO 0.73, Cl. 0.02.

VII. Center of Stop Island dike, Shutt, *loc. cit.*, p. 158, also intermediate analyses.

VIII. Center of White Fish Bay dike, 60 feet from contact, Shutt, *loc. cit.*

IX. Sp. 13459, kaolitic alteration of Sp. 13456, Sharpless, *loc. cit.*, p. 141.

X. Sp. 12966, kaolitic alteration; Aurora Mine, N. E. ¼, S. W. ¼, Sec. 23, T. 47. N., R. 47 W.; Chatard, *loc. cit.* with 0.38 CO_2; 0.08 MnO; tr. BaO. He also gives intermediate stadium analysis.

In Proc. A. A. A. S., 1875, B. p. 60, is an analysis from Lighthouse Point, Marquette, which may be a poor partial analysis of the dike. It agrees with the others in SiO_2, but there are a large number of greenstones of various ages on this point. See Pl. XV.

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* The second and third columns from the right on p. 105 refer to the table of correlations of conglomerates published by Marvine (Geol. Sur. Mich., I, Pt. II, facing p. 60.)