Nebel

The Duluth Gabbro and its Contact Metamorphism in the Vicinity of Gabimichigami Lake, Vermilion Iron-Bearing District, Minnesota

THE DULUTH GABBRO AND ITS CONTACT METAMORPHISM IN THE VICINITY OF GABIMICHIGAMI LAKE, VERMILION IRON-BEARING DISTRICT, MINNESOTA

BY

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The Duluth gabbro and its contact metamorphism in the vicinity of Gabimichigami Lake, Vermilion iron-bearing district, Minnesota.

by

Merle L. Nebel.

I. INTRODUCTION

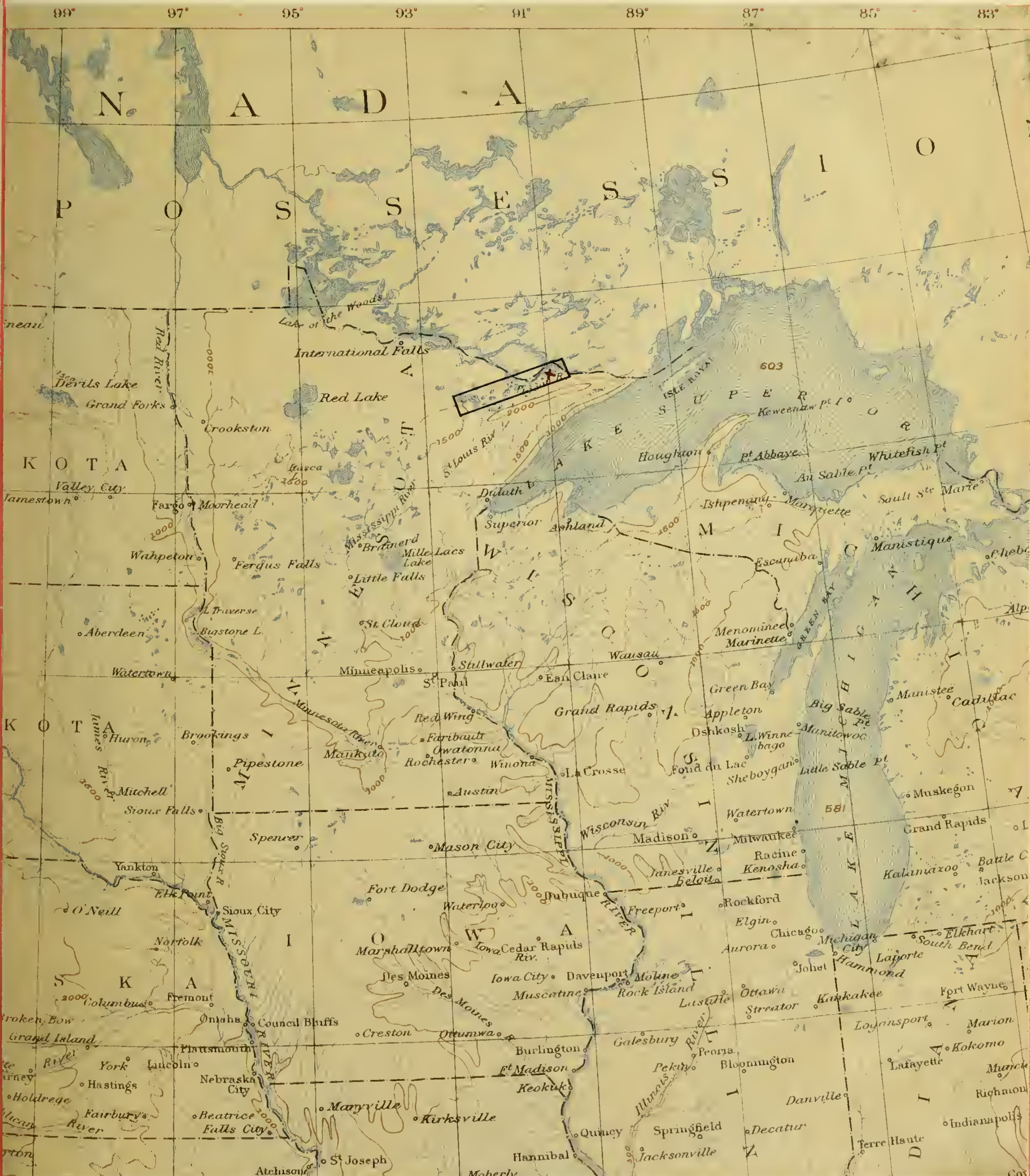
Statement of Problem.

This paper presents the results of a study of certain phases of the Duluth gabbro and the metamorphic effect which it has produced upon the older rocks intruded by it in the vicinity of Gabimichigami Lake, formerly spelled Gobbemichigamma, Vermilion iron-bearing district, Minnesota. This study consisted of two months field work in the eastern portion of the Vermilion district, and of a petrographic, mineralographic, and chemical study of material obtained in the field and from various other sources. The Duluth gabbro was studied in the field at several points along its south and west borders near Duluth, in the interior of the mass near Allen Junction, Minnesota, and along the northern border near Snowbank, Kekekabic, and Gabimichigami Lakes. The contact metamorphism was studied at the last three localities named. About a week was spent at Gabimichigami Lake, which offered the best opportunities for a detailed study.

Acknowledgements.

The writer is greatly indebted to Messrs L. E. Kennedy and C. S. Ross for assistance in the field and for many valuable suggestions and discussions during the course of the laboratory study; to Professor U. S. Grant of Northwestern University for suggestions in the field and for the loan of thin sections; to Professor W. H.

I-A.
Plate I



Key map

Vermilion Iron-bearing District

× Approximate location of Gabimichigami Lake

Emmons of the University of Minnesota for the loan of many thin sections from the collection of the Minnesota Geological Survey; and to Professor W. S. Bayley of the University of Illinois, under whose direction the work was done, for guidance and assistance throughout the course of the investigation, and for the loan of many thin sections.

II. HISTORY

The first mention of the geology of the region around Gabimichigami Lake occurs in the early reports of the Minnesota Geological and Natural History Survey. In the tenth annual report of that survey, in 1882, N. H. Winchell mentions finding the great conglomerate in the vicinity of Ogishkemuncie Lake, which has since been called the Ogishke conglomerate. The first study of Gabimichigami Lake was made in 1886, and described in the fifteenth annual report in 1887, pp. 375-381. In this report N. H. Winchell mentions the occurrence of a "quartzite-slate" formation along the north shore of the lake, and of a biotite gneiss along the east shore. He described the distribution of the rocks on the long point at the north end of the lake, afterward called "Muscovado Point", and gives a sketch map and cross-section. This section shows beds of the quartzite-slate series at the west end of the point, with a steep dip to the west. To the east the rocks have a low eastward dip, and are said to grade into a biotite gneiss, and then into a biotite diabase in the immediate vicinity of the gabbro, which is found at the extreme east end of the point. The quartzite-slate formation was regarded as belonging to the Animikie. In the same report (pp. 167-192) Prof. Alexander Winchell mentions various specimens collected on Gabimichigami Lake and gives a sketch showing "coarse gabbro poured over a huge pile of coarse, angular fragments of muscovodo."

In the sixteenth annual report in 1888, N. H. Winchell describes another visit to Gabimichigami Lake. In this report he mentions the occurrence of a gray feldspathic quartzite along the

south shore. He states (p. 91) "it becomes converted into a biotite gneiss in large part, similar to that seen on the Kawishiwi, and in that condition it acts like a matrix, rotting and crumbling and allowing round pieces of hard gray quartzyte to fall out and roll down to the beach." This was evidently the pseudo-conglomerate described later by Clements, the origin of which is discussed on p.   of this report. He described the occurrence on the south shore of a basalt dike showing columnar parting. He ascended the greenstone hill southwest of the lake, and became convinced that the hill was "made up mainly of modified beds, perhaps of the Animikie, but that they have been in almost a plastic state, and probably toward the summit were mingled with a truly eruptive greenstone without free silica, and without traces of sedimentary structure and composition."

In the seventeenth annual report in 1889, H. V. Winchell mentions a visit to a reported occurrence of iron ore on the southeast side of Gabimichigami Lake, and states (p. 111) "No extensive deposits of high grade or even medium grade ore were found."

In the nineteenth annual report in 1892, W. S. Bayley describes (pp. 193-210) certain rocks which occur a few miles east of Gabimichigami Lake, and had been called the Pewabic quartztite by N. H. Winchell, and shows that they are for the most part fine-grained granulitic gabbros, and are to be regarded as peripheral phases of the Duluth gabbro. They cannot, therefore, be considered as markers of definite horizons in the Animikie, as had been assumed by Winchell.

In the twenty-first annual report in 1893, N. H. Winchell

and Grant describe various specimens and thin sections of the rocks which have been called "muscovado". including several from Gabimichigami Lake, (pp. 146-148) and conclude (p. 152) "that the term muscovado rock (or muscovadyte) has been applied in the field to rocks of different stratigraphic position and origin.......... It is also apparent that one of these is produced by the action of the gabbro on the sedimentaries. It appears also probable that the southern belt of muscovado is a phase of the gabbro proper."

In the twenty-second annual report in 1894 Grant (p. 75) concludes that the so-called Pewabic quartzite of the Akeley Lake region east of Gabimichigami Lake is in reality a part of the Gunflint iron-bearing formation of the Animikie. In the same report Elftman (p. 169) adduces further evidence to the same effect.

In the twenty-fourth annual report in 1899, the last of the annual reports of this survey, Grant records numerous field observations made in the vicinity of Gabimichigami Lake (pp. 125-128). Of particular interest is a biotitic rock on the north shore of the bay in the SW ½ of Section 1, T. 64 N., R. 6 W., which is regarded as a contact phase of the Keewatin greenstones.

In 1899, volume 4, of the final report on the geology of Minnesota appeared, and in it are summarized the observations recorded in the ~~previous~~ annual reports previously referred to. Volume 5 appeared in 1900, and in it are summarized the observations on the structural geology and the descriptions of the rock specimens studied.

In 1900 Grant's paper on "Contact metamorphism by a basic igneous rock" appeared in the Bulletin of the Geological Society of America, Vol. 11, pp. 502-510. In this paper he discusses the

metamorphic effects of the Duluth gabbro, with special reference to the Gunflint iron-bearing formation. He concluded that the metamorphism consisted principally in a recrystallization of the materials present in the rocks, without any appreciable contribution of material from the gabbro.

In 1903 Clement's monograph on the Vermilion iron-bearing district appeared (Mono. 45, U.S.Geol. Survey). He also concluded that the metamorphism by the gabbro took place without appreciable contribution of material by the gabbro to the surrounding rocks. His conclusions and his discussions of the geology of the region around Gabimichigami Lake are discussed in detail in the body of this report.

Zapffe studied the metamorphic effect of the gabbro on the Gunflint formation in the vicinity of Gunflint Lake, and published his results in Economic Geology, Vol. 7, pp. 145-178, 1912. He likewise concluded that no addition of material took place. His results are discussed in detail in the body of this report.

III. GENERAL FEATURES

Location and accessibility of the region.

Gabimichigami Lake is situated in Lake and Cook counties in northeastern Minnesota, near the east end of the Vermilion iron-bearing district. It is about eight miles south of the international boundary line, and is in the heart of an unsettled region frequented only by trappers and sportsmen. It can be reached only by canoe, and the most convenient points at which the necessary outfits can be obtained are Ely, the center of the iron-mining industry of the district, and Winton, a lumbering town four miles east of Ely.

The lake is crossed by the lines between Townships 64 and 65 North, and Ranges 5 and 6 West, approximately one-quarter of its area lying in each of the four townships. The area studied in detail by the writer covers about four square miles in the immediate vicinity of the lake, including portions of Sections 29, 30, 31, and 32, T. 65 N., R. 5 W., Section 36, T. 65 N., R. 6 W., Section 1, T. 64 N., R. 6 W., and Sections 5 and 6, T. 64 N., R. 5 W.

Stratigraphy.

The rocks of the Vermilion district are of pre-Cambrian age, except for a small amount of drift, and are non-fossiliferous. The stratigraphic succession, according to the latest report of the U. S. Geological Survey *, is as follows:

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*Van Hise and Leith, Geology of the Lake Superior region, Mono. 52, U. S. Geol. Survey, p. 118, 1911.

Quaternary system:

Pleistocene series ------- Drift.

Unconformity.

Algonkian system:

Keweenawan series -------- Duluth gabbro and Logan sills.

Unconformity.

Huronian series:

Upper Huronian (Animikie group)	Rove slate Gunflint formation (Iron-bearing).
Unconformity	
Lower-middle Huronian	Intrusive rocks: Granites, granite porphyries, dolerites, lamprophyres Knife Lake slate. Agawa formation (iron-bearing) Ogishke conglomerate.

Unconformity.

Archean system:

Laurentian series	Granite of Basswood Lake and other intrusive rocks.
Keewatin series	Soudan formation (iron-bearing). Ely greenstone, an ellipsoidally parted and largely volcanic rock.

Of these formations only the following are present in the vicinity of Gabimichigami Lake:

Duluth gabbro and Logan sills, together with acid and basic dikes intrusive in the gabbro.

Gunflint formation.

Knife Lake slate.

Ogishke conglomerate.

Ely greenstone.

In addition to these, a quartzite formation was found on Gabimichigami Lake which is believed to be the basal quartzite of the

Upper Huronian, corresponding to the Pokegama quartzite at the base of the Upper Huronian in the Mesabi district to the south and west.

All of the above formations are well exposed along the shores of the lake, except the Ogishke conglomerate. Their distribution is indicated on the accompanying map. (Plate II). The lake lies on the contact between the Duluth gabbro and the pre-Keweenawan rocks which it intrudes, so that in a general way gabbro lies to the east and south of the lake, and the older rocks to the west and north.

Topography.

The topography of the region in the vicinity of Gabimichigami Lake is the result of glaciation, modified by the character of the different rocks, and by the structure. The lake lies a little south of the Giants range, and to the north and west the surface is somewhat rugged, but to the south and east lies the great gabbro plateau*, whose surface is rolling, with relief seldom more than 100 feet. There are no streams of any size in the vicinity, the drainage being taken care of by tiny trickles of water which carry the overflow from one lake to another. The surface of the lake is at an elevation of 1590 feet above the sea level, and the maximum relief is about 400 feet.

*Clements, J. M. The Vermilion iron-bearing district, Minnesota, Mono. 45, U. S. Geol. Survey, p. 37, 1903.

Relation of topography to structures and underlying rocks.

Northeast of the lake is a large hill of Ogishke conglomerate, and overlooking the lake along its southwest side is a rugged hill

of greenstone. Both of these rocks are hard and resistant. The greenstone hill is at the east end of a bold east-west ridge formed by the Twin Peak Archean anticline. Along the southeast and south side of the lake appear the rounded hills which are so characteristic of the surface underlain by the gabbro. Grant* ascribes the

*Grant, U. S. Geology of Minnesota, Minnesota Geol. and Nat. Hist. Survey, Final Report, Vol. 4, p. 435, 1899.

plain-like character of the gabbro plateau and the uniformity of the topography to "weathering, erosion, and glaciation acting on a surface composed of a single rock mass (the gabbro) uniform in constitution, grain, and resistance to disintegrating agents." It is along the east shore of the lake that the long, smooth gabbro cliffs, whose appearance suggest the existance of faulting, occur. (See Pl. V-B).

Erosion has been especially effective along the contacts of different formations, such as the contact between the greenstone and the slate formation, or the gabbro and the slate formation, and it is rarely that contacts can be located exactly, for the ground is usually low and swampy, and exposures lacking.

Exposures.

Exposures are good along the shores of the lake, except in the vicinity of contacts between formations. Away from the shores, however, exposures are scarce except along the tops of sharp ridges or along sharp cliffs, owing to the luxuriance of the forest and the covering of lichens and moss over everything. Over considerable areas in the Vermilion district, forest fires have completely denuded the rocks of vegetation, and they lie beautifully exposed,

in excellent condition for the most detailed geological examination. The Gabimichigami Lake region was densely forested, principally by second growth, when visited by the writer.

Soil, Forests, Game, and Fish.

The soil is very thin in this region, and is practically lacking over the areas of greenstone, slate, and conglomerate, for these rocks are thoroughly jointed, and disintegrate rapidly into angular blocks which are very slowly attacked by weathering agencies The gabbro disintegrates and weathers rapidly, and forms a coarse gravelly soil.

The trees of the region are principally poplar, jack pine, and birch, with an occasional small white pine or a Norway or red pine, and with clumps of balsam, fir and spruce. In swampy places are also found cedar, swamp ash, and occasionally a tamarack.

Game is fairly abundant in the region, although it has been frequented by sportsmen for years. Deer and moose are common, but caribou, which were reported to be abundant about twenty years ago, are very rarely seen at the present time. Bears are not uncommon.

The common fish in the district are pickerel, wall-eyed pike, lake trout, and bass, but only lake trout were taken by the writer's party from Gabimichigami Lake.

V. PETROLOGY

re-Algonkian

ELY GREENSTONE.

Clements* says "The rocks comprised in the Ely greenstone

*Clements, J.M. The Vermilion iron-bearing district, Minnesota, Mono. 45, U.S. Geol. Survey, p. 136-137, and 151, 1903.

originally corresponded in character to intermediate andesites and basic basalts...... Most of the changes which have affected them have been in the character of the minerals...... The macroscopic textures commonly seen are the ophitic, the poikilitic, and the porphyritic. The rocks possessing these textures vary from fine-grained, almost aphanitic, ones to those which are very coarse-grained and, in exceptional cases, have some constituents an inch and a half in length. Many of the finer-grained forms of these rocks are amygdaloidal and also frequently show beautiful cases of spherulitic development.

"Good columnar parting is totally wanting in the greenstones of the Vermilion district, but, apparently taking its place, ellipsoidal parting is abundantly present. All combinations of the above structures and textures may be found in this complex and all gradations between the rocks possessing them.

"The original minerals that remain are few. The microscope discloses the following original constituents: Hornblende, augite, feldspar, quartz, titaniferous magnetite, and apatite...... The secondary constituents are common green hornblende, actinolite, chlorite, sericite, epidote, zoisite, sphene, rutile, feldspar, quartz, pyrite, and hematite. The feldspar has usually altered to a mass of sericite, kaolin (?), feldspar, and quartz. In some

cases it is completely saussuritized. There were observed occasional irregular but in general rounded serpentinous areas, which are strongly suggestive of aggregates of olivine individuals in which the olivine possesses no definite crystallographic outline.

"In the coarse-grained rocks the ophitic texture predominates; in the even-textured, fine-grained rocks the following are commonly developed: ophitic, microophitic, intersertal, pilotaxitic, hyalopilitic, flowage, and spherulitic textures."

The greenstones near Gabimichigami Lake are for the most part massive amphibolites. They are all fine-grained, and are light gray, light green, dark green, or dark gray to almost black in color on fresh fracture. They are never distinctly schistose, and seldom show any banding or parallel structures, although occasionally a slight banding may be seen, suggestive of a poorly preserved flow structure. Columnar parting is entirely absent, and only occasionally can one recognize the ellipsoidal parting so well developed in some places in the Ely greenstone. Amygdaloidal structures occur sometimes, but are not abundant. The spherulitic structure also seems to be entirely absent. The texture of most of the amphibolites is distinctly ophitic. Porphyritic texture is sometimes seen. The mineral constituents are principally hornblende and plagioclase, although both calcite and chlorite can sometimes be recognized.

Microscopic characters.

In thin section the ophitic texture is often very marked. The plagioclase is usually lath-shaped in outline, although never with the sharpness of outline shown in fresh diabases. Usually the borders of the laths are serrate and are penetrated irregularly by the hornblende.. Hornblende is frequently developed as needle-

like inclusions in the plagioclase, often aligned along the center of the laths. Where the laths are well preserved the plagioclase is labradorite or andesine (about $Ab_{40}An_{60}$ to $Ab_{60}An_{40}$). In some sections the plagioclase has been recrystallized to a fine mosaic of acid andesine grains, the aggregates retaining rough lath-shaped outlines. In these ophitic rocks the only other constituent of importance is a pale-green, common hornblende. It occurs in anhedral and often shred-like forms between the feldspar laths, and in aggregates intergrown with granoblastic andesine. Occasionally a little quartz occurs in a fine mosaic of grains intergrown with hornblende and feldspar. The feldspar when recrystallized into a mosaic of small grains is usually quite fresh, but the twinned laths of labradorite or andesine are usually turbid and altered with the development of epidote, calcite, zoisite, and chlorite. Magnetite is often present in small grains.

The relative proportions of the constituents vary, but the ophitic amphibolites usually contain from 50 to 70 per cent of hornblende, and 30 to 50 percent of plagioclase with small amounts of the other constituents.

Although no chemical analyses are available, the texture and mineralogical composition of these rocks indicate that they are probably old basalts of supra-crustal origin which have been metamorphosed under conditions such as those of the "meso-zone" of von Grubenmann,* and they belong among his "plagioclase amphibolites".

*Von Grubenmann, Die kristallinen Schiefer, p. 202, 1910.

The porphyritic amphibolites often show excellent preservation of the porphyritic texture, although the rocks have been com-

pletely changed to a mass of chlorite, green hornblende, colorless or pale green actinolite, epidote, calcite, magnetite and quartz. Occasional relicts of plagioclase phenocrysts still persist, sometimes showing indistinct twinning lamellae, but they are very turbid and much altered to a saussuritic aggregate of secondary minerals. Other relict phenocrysts have the outline of idiomorphic crystals of hornblende, but the original hornblende is entirely altered to a mass of chlorite, calcite and quartz, or of actinolite and calcite. The groundmass is so completely altered to the secondary minerals enumerated above that its original character cannot be determined. The rocks are evidently old andesite or basalt porphyrites.

Algonkian

OGISHKE CONGLOMERATE.

Although varying in coarseness from grits to a coarse boulder conglomerate with boulders two or three feet in diameter, by far the greater portion of the Ogishke conglomerate is represented by a coarse-grained rock with pebbles and boulders of perhaps 8 to 10 inches maximum diameter. The conglomerate found near Gabimichigami Lake is identical in character with what Clements calls the typical Ogishke, as found at the type locality on Ogishkemuncie Lake, and is probably a portion of the same mass. The rock is characterized by the presence of abundant bright red jasper pebbles which give it a striking appearance, but it also contains an abundance of pebbles of clear quartz, feldspar, pink and gray granite, two or three kinds of porphyry, greenstones, etc. The rock is thoroughly indurated, and the pebbles do not easily break out the matrix as a rule, but fractures pass through pebbles or matrix indiscriminately. This induration is partly the result of infiltration of silica, and is due partly to recrystallization of the rock by which some minerals have been enlarged (feldspar) and new minerals have been produced.

The matrix is light green or gray in color and is entirely similar to the graywackes in character. It has recrystallized, and consists of abundant light green hornblende in shreds and fibers and sometimes in well-developed anhedral grains lying in a granoblastic mass of quartz and albite grains with smaller amounts of actinolite needles, epidote, zoisite, and magnetite. Many of the quartz and feldspar pebbles have recrystallized to a

granoblastic aggregate, and many of the rock fragments have been reduced to aggregates of hornblende and albite, albite, quartz, and chlorite, etc., but usually without destruction of the fragmental outlines. Other minerals have developed near the gabbro as the result of contact metamorphism, described elsewhere.

KNIFE LAKE SLATES.

Clements* says of the Knife Lake slates (p. 293), "It has

*Clements, J. M., The Vermilion iron-bearing district, Minnesota, Mono. 45, U. S. Geol. Survey, p. 293, 1903.

been stated that the dividing line between the Ogishke conglomerate and the Knife Lake slates is purely arbitrary. The transition between them is not sharp. Among the conglomerates there are a few interbedded fine-grained sediments, and among the slates there are a few fragmentals that are coarser than the normal slates, and show gradations between the slates and the conglomerates. However, the slates are by far the predominant kind of rock in the areas marked on the accompanying maps with the slate color, the grits playing a very subordinate role.

"Corresponding to differences in mineralogic character there is in the slates considerable variation in color and texture. The normal slates are on fresh fracture generally a slate gray to dark greenish gray, and even light greenish. Sometimes they rn range through purplish and bluish-black rocks to a dense and almost black slate. They usually weather with a light-gray to brown crust. The grain of the slates is so fine that one can distinguish no individual mineral, unless it be quartz, except in the phase that approaches the grits. The banding in the slates is caused

by slight variations in the quantity of the minerals of different color constituting the slates, and by a slight difference in the size of grain. These bands within the slates vary in thickness from a fraction of an inch to several feet. The bands of slate themselves, where interlaminated with grits and near the conglomerates, also vary in thickness from a few inches up to 30 paces. These slate beds show a gradual increase in thickness as they occur at a greater distance from the conglomerates.

"Microscopic examination of the Knife Lake slates and associated graywackes shows that the primary constituents are feldspar, quartz and hornblende in fragments. With these occur secondary products---chlorite, epidote, calcite, sericite, sphene, and pyrite. In the coarse-grained rocks the various constituents can readily be distinguished. In the finer grained ones only the coarser particles can be clearly recognized, and these lie in a very fine-grained dark matrix whose characters cannot be positively determined but which probably consists of fine dust particles derived from the other constituents, with which may occasionally be associated some carbonaceous material (although this was not recognized as such) and ferruginous matter, the last being the chief cause of the dark color.

"These slates vary from the normal slates described, which preponderate, to rocks found in certain portions of this area, which, although showing all the macroscopic features of bedded clastics, nevertheless under the microscope are seen to have been recrystallized, and now may properly be called mica--and amphibole-schists and gneisses."

Near Gabimichigami Lake, the Knife Lake slate series consists of interbedded slates and graywackes which are not particularly different from the great mass of such rocks occurring elsewhere in the Vermilion district. They grade into the coarse Ogishke conglomerate north of the lake.

Along the southwest shore of the lake, near the greenstone area, the slates are very fine-grained, and are light gray to light green in color. The green color in this case is due to the presence of variable amounts of pale green diopside, which may be recognized under the microscope. Feldspar is the most abundant constituent, but is so turbid and altered that its composition could not be estimated. The other minerals present are quartz, calcite, epidote, zoisite, and a little pale green hornblende.

Farther north, especially between Fox and Agamok lakes, the slates are extremely fine-grained, and on fresh fracture are a dead black with almost the appearance of cannel coal. They weather with a thin, white or light gray crust, and on weathered surfaces the bedding planes are strongly accentuated. All of the fine-grained slates break with a smooth conchoidal fracture irrespective of the position of the bedding planes, and on fresh surfaces show no sign of such planes.

Passing northward one crosses the series of slates and graywackes, the slates becoming coarser, and being interbedded with graywackes and grits. The graywackes are nearly always light gray in this region, seldom dark gray. One can recognize macroscopically pebbles and angular grains of feldspar, quartz, green hornblende, and sometimes small pebbles of greenstone, and small

pebbles of greenstone, and small flakes of biotite. Bedding is seldom as distinct as in the fine-grained slates, but can sometimes be recognized.

Microscopic Characters.

The microscopic characters are those of a poorly sorted clastic which has been partially recrystallized without the destruction of the clastic texture. The fragmental character of the graywackes is readily discernible by observation in ordinary light. Angular and sub-angular fragments, often with sharp outline, of quartz, orthoclase, acid and basic plagioclase, and in the coarser grits, of greenstone, granite, acid and basic porphyries, etc., lie in a matrix of very fine-grained material of the same sort with the addition of a pale green to brownish green hornblende. The hornblende occurs as needles and shreds throughout the groundmass, and in large and small poikilitic individuals with irregular outlines which enclose indiscriminately portions of the groundmass, and sometimes encroach on the larger fragments. Biotite is present in many sections, but its presence is probably due to the contact effect of the gabbro which is described elsewhere. Magnetite, apatite, calcite, muscovite, chlorite, and epidote are often present in small amounts. The larger fragments of quartz are sometimes partially or completely recrystallized into a mosaic of small grains occupying the area of the original grains so that in ordinary light each fragment appears to consist of a single grain.

A partial analysis of a medium-grained slate was made for

the writer by J. M. Lindgren, with the following result:-

$Si\ O_2$	69.33
$Al_2\ O_3$	15.67
$Fe_2\ O_3$	7.63
$Ca\ O$	1.51
$Mg\ O$	0.20

ANIMIKE QUARTZITE.

The rock which is here interpreted as the basal quartzite of the Upper Huronian has been very thoroughly metamorphosed by the gabbro and practically everywhere that it was found it contained a noticeable amount of brown biotite. It has been called mica schist or mica gneiss, but very rarely was any schistose or gneissic structure noted by the writer or any parallel arrangement of minerals. It is also one of the rocks which were called "muscovadite" by N. H. Winchell.

It usually occurs in flat-lying beds with a low dip to the southeast, but at one point rather sharp folding on a small scale was noticed. On the west side of the small island which is crossed by the line between Townships 64 and 65 N small small folds a few feet across were seen. At all other places the beds were only slightly tilted. At several localities the quartzite has a decidedly conglomeratic appearance, with pebbles as much as five or six inches in diameter. Careful study was made of the pebbles to ascertain their character and it was found that they always consisted of the same material; a dense, fine-grained quartzite containing very little or no mica. The matrix consisted of coarser material, principally quartz and feldspar, with abundant mica flakes. This

same feature was noted by Clements* who explained it as follows:

*Clements, J. M., The Vermilion iron-bearing district, Minnesota, Mono. 45, U. S. Geol. Survey, p. 344, 1903.

"At some distance away from the gabbro contact rounded masses of dense greenish and gray rock begin to appear, surrounded by the granular contact product. This gives a conglomeratic appearance to the exposure. A little farther away from the gabbro, on a vertical exposure at the lake shore, these pebble-like areas were seen to be aligned, and eventually to pass into parallel unbroken bands. The explanation of this occurrence is that the gabbro in contact with the sediments caused them to be altered to the peculiar granular contact product. The alteration was naturally most effective nearest the gabbro, and gradually spread, following along the cracks in the rocks, the vertical as well as the horizontalcracks. Near the gabbro all of the sediments were changed. Farther away the blocks or fragments were changed on the exterior most completely. Sometimes this change was so far-reaching as to convert into granular contact product most of the sedimentary block, and to leave only a small core of this block, but even this was very much modified. Such a core looks like a pebble in a matrix, and gives the rock a conglomeratic appearance."

This explanation is, in general, in accordance with the features noted by the writer, but the process was probably a little more complicated. There is some evidence, that the lack of alteration of the pebbles is due in part to an initial difference in character. At the place where the folding mentioned above was observed it was noted that narrow bands of fine-grained, dense quartzite were broken up along the limbs of the folds into small

blocks, while the coarser, more impure material in layers on either side were unbroken. The nearly pure quartzite layers lacked the elements necessary for the formation of biotite, when the intrusion of the gabbro took place, while the ill-sorted, impure quartzite or graywacke layers readily recrystallized, and abundant biotite flakes were produced.

The process was not quite as simple as that of simple alteration along the bedding planes and cracks, decreasing away from the gabbro. At three different localities the pebbles were studied with respect to the orientiation of their bedding planes, and it was found that they were not aligned. The bedding planes were oriented at random, with the pebbles twisted in any direction. Evidently movement was an important factor. It seems probable that some folding and crumpling of the beds took place at the time of the intrusion of the gabbro, resulting in the fracturing of competent layers, and the flowage of the softer, more incompetent layers around the fractured blocks. This is supported also by the fact that many of the pebbles do not grade into the matrix, but break out sharply, as a conglomerate boulder breaks out of its matrix. In some cases, however, pebble-like masses of dense non-micaceous rock grade into the micaceous matrix material.

The Animikie quartzite is light gray, greenish gray, or brownish gray, and varies from a very fine-grained, non-micaceous rock with almost conchoidal fracture to one which contains an abundance of poikilitic plates of brown biotite a centimeter or more across, and appears to be quite coarse-grained. On close examination this coarse-grained appearance is seen to be due to the abundance of mica plates which are oriented at random and

cause the rock to be very friable and to break up into coarse lumps. The minerals other than biotite are seldom more than a millimeter in diameter, so that there is not so much variation in coarseness as appears at first. The pebbles of the pseudo-conglomerate are usually of the dense, fine-grained, non-micaceous quartzite, while the matrix is slightly coarser-grained and very micaceous. Occasionally the matrix is slightly schistose and curved around the pebbles, but for the most part schistose structure is entirely lacking. The mica plates lie at all angles and were evidently formed by recrystallization under mass static conditions.

Microscopic Characters.

Between thirty and forty sections of the quartzite were studied and the following minerals were recognized: Quartz, feldspar (including orthoclase, and plagioclases from albite to labradorite), biotite, cordierite, calcite, hypersthene, diopside, light green hornblende, colorless actinolite, muscovite, chlorite, magnetite, titanite, rutile, zircon, apatite, serpentine, pale-blue tourmalin, deep-blue tourmalin. The first three are always present, are nearly always the predominant minerals, and are frequently the only constituents except for a small amount of secondary minerals.

The quartz is nearly always the most abundant mineral, although feldspar is always present in greater or less amount. It's original rounded outlines are seldom preserved, recrystallization always having taken place to a greater or less extent. Sometimes this process has merely attacked the borders of the larger grains and given them a serrate contour, with a matrix of small grains in a fine mosaic. (Pl. VII A). In most cases, however, the process has gone so far that the quartz is completely recrystal-

[illegible]

[illegible]

[illegible]

[illegible]

lized into large interlocking grains which entirely enclose the other constituents present. (Pl. VII B).

Feldspar, although always present, is nearly always subordinate in amount to the quartz, but an occasional band of the rock is made up principally of feldspar. Both orthoclase and plagioclase are usually present, and the plagioclase varies in composition from albite to labradorite. Near the north end of the area the orthoclase and acid plagioclase are the characteristic feldspars, but near the Archean Greenstones, andesine and labradorite are common constituents. The feldspar is seldom recrystallized, but usually lies between the quartz grains in small groups of rounded or subangular grains, which are nearly always partly altered to muscovite. Sometimes feldspar grains have been enlarged by the addition of material to them in optical continuity with the original grain. (Pl. VIII A) Occasionally complete recrystallization has taken place and feldspar grains form a mosaic with the quartz. The plagioclase in particular usually remains uncrystallized, and the large recrystallized quartzes often enclose rounded grains of that mineral which are partly altered to mica and show no signs of recrystallization. (Pl VII B).

The biotite is the third mineral which is always present. The fine-grained denser quartzites contain only a few flakes of it, but the coarser rocks have it in great abundance. In these it is usually developed as large poikilitic plates which enclose indiscriminately rounded grains of any of the other minerals. It is always a deep reddish-brown variety with very strong absorption. X light yellow, Y and Z deep reddish brown to black. The color is much more reddish than that of the brown biotite in the gabbro.

Inclusions of idiomorphic apatite crystals and rounded zircons with strongly pleochroic halos are common, and the halos are of unusual size. Those around zircon have a radius of as much as .056 mm. The biotite undoubtedly has a high titanium content. It alters to a mass of colorless chlorite which is crowded with a sagenitic web of rutile needles. Sometimes the rutile is so abundant as to form a mass which is almost perfectly opaque with a few slender threads of chlorite parallel to the original biotite cleavage. In some sections the biotite is completely altered to this material, and its nature is extremely puzzling unless one has previously seen sections of the biotite arrested in the process of alteration, for the rutile needles are sometimes so small and so densely packed together that individual needles cannot be seen. (Pl. VIII B) This is the material referred to elsewhere (p.) which was so puzzling to Winchell.

Cordierite is a common constituent in the metamorphosed quartzite. Grant and N. H. Winchell* early recognized this mineral

*Winchell, N. H.. and Grant, U. S., the Geology of Minnesota, Minnesota Geol. and Nat. Hist. Survey. Final Report, Vol. 5, p. 657, 1899.

in rocks metamorphosed by the gabbro. A. N. Winchell** in 1900

**Winchell, A. N.. The Gabbroid rocks of Minnesota, Amer. Geologist, vol. 26, pp. 294-306, 1900.

described cordierite norites which were believed to be border phases of the gabbro, and Zapffe*** in 1912 described metamor-

*** Zapffe, Carl, Effects of a Basic igneous intrusion on Lake Superior iron-bearing formation, Econ. Geol. vol. 7, p. 145-178, 1912.

phosed greenstones, metamorphosed iron formation, and metamorphosed gabbro containing large percentages of cordierite.

In the Gabimichigami quartzite the cordierite is abundant only in those parts which have been thoroughly recrystallized, and it occurs in little twinned prisms, many of which are completely enclosed in a single quartz grain.(Pls. VII B and VIII B) The cordierite is sometimes quite fresh, but in most sections it is partly or completely altered to a mass of tiny muscovite flakes. (Pl. VIII B) The alteration to mica begins around the borders of the prisms, and proceeds inward along cracks, especially along parting planes parallel to the base. A few sections consisted almost entirely of quartz and these mica pseudomorphs after cordierite (pinite), together with a few poikilitic biotite plates, the cordierite sometimes making up 40 or 50 per cent of the rock. Occasionally quartz, plagioclase, and fresh cordierite occur together in a fine mosaic of polygonal grains. In one or two sections large cellular grains of cordierite were found enclosing rounded quartz grains. They are very similar to the cordierite described by Eskola* in the cordierite gneisses of the Orijärvi Region, Finland.

*Eskola, Pentti, Petrology of the Orijärvi region, Finland, Bull. No. 40, Comm. Geol. de Finlande, p. 167-212, 1914. See also Plate V. Fig. 2.

The sections were compared with sections of the Finland rocks (cut from specimens presented to the University of Illinois by Eskola), and the similarity is striking.

Calcite is present in most sections of the quartzite. It is in part an alteration product of plagioclase, but in some sections it is quite abundant and seems to have been an original constituent of the rock. It occurs as little irregular grains uniformly distributed throughout the rock, forming a mosaic with quartz. (Pl. IX-A) Again the calcite is in large grains surrounding and enclosing quartz. The larger grains sometimes show

the twinning bars which are produced in calcite which has been subjected to great pressure.

Hypersthene occurs in small amount in two or three sections, as small rounded grains or small porphyroblasts partially enclosing a few quartz grains. It was never present in greater abundance than three or four per cent.

Colorless diopside, colorless or pale-green actinolite, and light-green hornblende occur in a few sections, but they are never abundant. The diopside forms little rounded grains which are partly altered to green serpentine, or to green hornblende. The colorless actinolite occurs in one or two sections as a few skeleton porphyroblasts enclosing grains of the other constituents. The light green hornblende forms little irregular grains which are probably alteration products of augite, and also occurs in irregular shreds and fibrous masses between the other minerals. Muscovite occurs as tiny flakes resulting from the alteration of feldspar or cordierite. Chlorite occurs as an alteration product of biotite and is abundant in some sections. It is a pale-green or yellow penninite with the blue interference colors commonly exhibited by that mineral. Serpentine is sometimes an alteration product of augite, but is present in very small amount. Magnetite and titanite occur as accessories in a few sections but are rare or absent in most cases. The titanite occurs as little round or oval grains and groups of grains resembling the forms called "insect eggs", by Weinschenk.* Rutile, zircon, and apatite occur in nearly every section, the zircon and apatite as little rounded

*Weinschenk, Petrographic Methods, trans. by Clarke, p. 256, 1912.

crystals, and the rutile in sagenitic webs resulting from the decomposition of biotite. (Pl. VIII-B)

A majority of the sections studied contain blue tourmaline. In a few cases the tourmaline is a pale-blue variety and occurs in very slender crystals or radiating groups of crystals. O colorless, and E pale blue. In most cases, however, the tourmalin is a deeper-blue variety, with O colorless, and E deep blue, and occurs in isolated stout prisms or in allotriomorphic grains.

Clements reports the presence of olivine in the contact-metamorphosed slates*, but no olivine was recognized by the writer in any of the sections of metamorphosed quartzite, nor for that matter in the metamorphosed slates.

*Clements, J. M. The Vermilion iron-bearing district, Minnesota, Mono. 45. U. S. Geol. Survey, pp. 344 and 345, 1903.

Partial analyses were made for the writer of two specimens of the metamorphosed quartzite with the following results:

	366	373
$Si\ O_2$	61.85	65.71
$Al_2\ O_3$	19.32	15.58
$Fe_2\ O_3$	9.06	4.56
Ca O	3.50	4.81
Mg O	1.74	1.15

J. M. Lindgren, analysist.

GUNFLINT IRON-BEARING FORMATION.

The Gunflint iron-bearing formation is represented in the Gabimichigami Lake region only by beds which have been very thoroughly metamorphosed by the Duluth gabbro. The maximum distance from the main gabbro mass at which they have been observed is only

about one-fourth mile and at this locality metamorphism has been so thorough that the rocks consist of a mass of complex silicates, and nothing remains to indicate their original sedimentary nature except their bedding. These rocks have been studied by the geologists of the Minnesota Geological Surveys, and the U. S. Geological Survey, and correlated with the Gunflint formation in the vicinity of Gunflint Lake where the relations are clearer. This formation has been correlated with, and is practically the eastward extension of the Biwabik iron-bearing formation of the Mesabi district.

On most of its exposures the iron-formation is badly weathered to a loose brownish soil, or a crumbling, iron-stained mass of rock, but where it is fresh it is beautifully banded. The bands vary from a fraction of an inch to several feet in thickness, and are composed of a great variety of minerals of widely different chemical nature. Many of the bands are sharp and well-defined. Others grade into each other by gradual decrease in amount of one mineral and increase in amount of another, or by subtraction of one mineral or addition of another.

Some of the bands consist almost entirely of coarsely-granular, grayish, brownish, or greenish vitreous quartz resembling a very coarse quartzite with a small amount of interstitial material. This interstitial material may be pink or brownish garnet, honey-yellow to light brown olivine, or greenish or brownish, fibrous amphibole. Adjacent to the quartzose band may be one consisting almost entirely of olivine, or of olivine and quartz, or of olivine and magnetite, or of olivine and magnetite and a greenish pyroxene.

Other bands consist almost entirely of magnetite; others of green pyroxene in finely-granular mass or in coarse grains as much as a half inch in diameter and with excellent cleavage; others of brownish bronzite with a high luster, and in large platy masses whose cleavage faces often show uniform reflection of light over an area an inch or two in length and perhaps a half-inch wide; others of brownish, fibrous anthophyllite. Bands were found which consisted almost entirely of cordierite in a vitreous, granular mass which is a brilliant violet or blue by reflected light, and in thin chips is translucent with a clear violet or blue color. Almost any combination of the above minerals may be found in a single band, although the above combinations are the most important ones observed. These bands of greatly variable mineral and chemical composition may show great variation in width, and almost any of such bands may be adjacent to or grade into one another. It is almost impossible to obtain a quantitative idea of the mineralogical or chemical composition of the iron formation by a study of thin sections alone, since a thin section represents only a portion of a band, particularly of the wider bands, which may vary in itself. Chemical analyses could be of slight value unless very large samples were taken by cutting trenches at right angles to the direction of the bands. The size of such samples would have to be enormous in order to reduce errors in sampling to values at all commensurate with the analytical errors. If samples of a material as uniform in composition as coal (sampled by such a method) must weigh at least 60 lbs. for a ten foot bed,* one can

*Fieldner, A. C. Sampling and Analyses of Coal. Technical Paper, 76, U. S. Bureau of Mines, p. 8, 1914.

understand the necessity of taking large samples of a material which may vary from nearly pure silica to nearly pure iron-oxide, with widely different proportions of calcium, magnesium, aluminum, etc.

Microscopic Characters.

A great variety of minerals may be recognized in thin section. They are minerals which are produced by anamorphic processes under conditions like those of von Grubenman's "kata-zone" of metamorphism, the rocks show the crystalloblastic structures characteristic of rocks formed under such conditions, such as the sieve-structure, and the granoblastic, nematoblastic, and poikiloblastic structures. The following minerals were observed:

Quartz, garnet, calcite, magnetite, olivine, cordierite, hypersthene, bronzite, diopside, augite, anthophyllite, actinolite, green hornblende, cummingtonite, grunerite, blue tourmaline, biotite, chlorite, and serpentine. In addition to the above, Zapffe* has reported the following minerals from the Gunflint formation in the vicinity of Gunflint Lake:- Hedenbergite, pyrrhotite, diallage, pargasite, pleonaste, sericite, apatite, ilmenite, and crocidolite.

*Zapffe, Carl, Effects of a basic igneous intrusion on a Lake Superior iron-bearing formation. Econ. Geol. vol. 7, pp. 175-176, 1912.

The quartz occurs sometimes in rounded or polygonal grains of about the same size, between which lie grains of olivine, augite, anthophyllite, etc. Sometimes the interstices between the grains are occupied by very fibrous grunerite, slender fibers of which penetrate the quartz grains on all sides (Pl IX-B. It resembles

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

nothing so much as a quartzite whose matrix has recrystallized with the production of the complex silicates enumerated. In some sections, the interstices between the grains are filled with secondary quartz which acts as a cement, and there can be no doubt as to the clastic origin of the rock. The quartz grains are well rounded and show no sign of recrystallization. Sometimes the quartz has been recrystallized and occurs in very irregular grains enclosing and enclosed by garnet, cordierite, and calcite. (Pl X-A) Again it occurs as little rounded grains enclosed by bronzite in a cellular structure. Sometimes it occurs with olivine, forming a mosaic of small polygonal grains. (Pl X-B)

The garnet is yellowish or pink in thin section, and shows considerable variation in depth of color. Many grains are anisotropic and the anisotropic character seems to be connected with the depth of color. The pale-yellow grains are usually smaller and have a low birefringence, while the larger, deep yellow or pale-brown grains are for the most part completely isotropic. There is, however, variation in color in individual grains which are completely isotropic. The grains are of very irregular shapes and frequently enclose rounded grains of quartz, irregular angular grains of calcite, hornblende, etc. (Pl X-A) Calcite was noted most abundantly in those bands containing quartz and garnet. It occurs in grains with very irregular shapes which enclose or are enclosed by quartz, garnet, cordierite, colorless augite, green hornblende, etc. The larger grains frequently show lamellar twinning.

Magnetite is abundant in many bands of the rock and almost lacking in others. It is seldom in large grains, but in small

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[illegible]

[illegible]

[illegible]

rounded or polygonal grains which may be associated with any of the other minerals.

Olivine is a common constituent. It is frequently yellow or light brown in thin section and is certainly fayalite, but in other cases it is perfectly colorless or pale green, so that hyalosiderite and perhaps olivine (chrysolite) are also present. Fayalite is usually associated with magnetite or green diopside in a mosaic of small polygonal grains. Olivine (chrysolite) frequently occurs as inclusions in quartz, and sometimes these two minerals are practically the only constituents of certain bands of the rock. (Pl X-B) Sometimes olivine grains have a narrow rim of colorless diopside around them where they are in contact with quartz.

Cordierite is common in certain bands. Sometimes it is associated with quartz and intergrown with it in sieve-structure, the cordierite forming the web or matrix. Certain bands consist almost entirely of cordierite and hypersthene.(Pl XXVII A & B) In these bands the cordierite is pale blue in thin section, and faintly pleochrois, pale blue or colorless. It shows simple or repeated lamellar twinning, resembling plagioclase. The hypersthene is light green and is strongly pleochroic, in green and pink or yellow tints. It forms large poikiloblasts enclosing rounded grains of cordierite, in a matrix of polygonal cordierite grains.

Certain bands are composed entirely of large crystals of bronzite with cleavage faces an inch ot two in diameter, which enclose small rounded grains of quartz in beautiful sieve-structure. The bronzite is yellowish or gray in thin section, and

frequently shows a fine lamellar twinning.

Diopside is variable in composition, probably because of admixture with the hedenbergite molecule. It varys from a colorless variety with Z c 38, to a pale-green variety with Z c 38, and a quite deep-green variety with Z c 39-40. The deep-green variety is the most common and certain bands of the rock consist entirely of this mineral in little polygonal grains. No hedenbergite was observed.

The augite is a colorless variety and was noted in only a few of the sections.

The augite is a colorless variety and was noted in only a few of the sections.

The anthophyllite is colorless or grayish in thin section. It is associated usually with olivine or diopside, and is often accompanied by grunerite or cummingtonite. Some portions of the rock consist almost entirely of long, ragged grains of anthophyllite in a mass of fibrous grunerite.

The actinolite is colorless or pale green, and the green hornblende is dark green, but pleochroic in yellowish-to bluish-green tints. Neither is present in any quantity. The latter is in part secondary to augite, but is probably original in some cases. It was found completely enclosed in hypidiomorphic crystals by garnet and calcite.

Grünerite and cummingtonite are colorless or yellowish-to brownish, and are very slightly pleochroic. The former is much the more abundant of the two. They occur between quartz grains, penetrating the quartz in very tiny fibers (see Pl IX-B), and are also abundantly associated with anthophyllite. Small fibrous

flakes occur in small amount in almost every section.

Blue tourmaline is found occasionally. It is quite similar to that found in all of the other contact-metamorphosed rocks.

Occasionally a small flake of brown biotite may be seen, but it is very rare.

All of the minerals are quite fresh in most sections. Occasionally a little pale-green chlorite, and green to yellowish-brown serpentine may be seen. Recent weathering has resulted in the production of limonite and chalcedonic silica and occasionally veinlets of these minerals may be seen crossing a section of the more weathered specimens.

Keweenawan Igneous Rocks

DULUTH GABBRO.

The main mass of the gabbro in the vicinity of Gabimichigami lake consists of a basic, coarsely granular olivine gabbro. The color is dark brown or black on weathered surfaces, but on fresh surfaces is light gray, dark gray, brown, or almost black, the darker colors predominating in those phases in which the ferro-magnesian minerals are most abundant. The rock is usually coarse-grained, with plagioclase laths about 0.5 to 1.5 cm. long, but it varies locally from fine-grained granulitic phases with grains a millimeter or less in length to very coarse-grained, almost pegmatitic phases in which plagioclase and augite crystals are sometimes 10 to 15 cm. or more in length.

Gray plagioclase is usually the most abundant constituent, and with it in various proportions occur augite, hypersthene, olivine, magnetite, biotite, chalcopyrite and pyrrhotite. The plagioclase is practically always distinctly striated, and occurs in tabular crystals between which lie angular, often wedge-shaped, masses of the ferromagnesian minerals. The augite is dark brown or black, and never shows crystal outlines. The olivine is colorless or light yellow with a glassy appearance and occurs in irregular grains between the feldspars. Hypersthene when it occurs is light brown in color, has very poor cleavage, and is almost glassy in appearance with an irregular fracture. Magnetite is usually not abundant, and biotite occurs only as occasional flakes. Small grains of chalcopyrite and pyrrhotite may be seen at many localities, but have never been reported in large amounts.

Microscopic Characters.

Plagioclase is generally the most abundant constituent. It is a twinned labradorite, varying from about Ab_{50}-An_{50} to Ab_{35}-An_{65}. An analysis by Hillebrand of such a plagioclase from the Duluth gabbro is quoted by Bayley.*

*Bayley, W.S., Basic massive rocks of the Lake Superior region. Journal of Geology vol. 1, p. 701, 1893.

No.	SiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MgO	K_2O	Na_2O	H_2O	(100)
8786	51.89	29.68	.32	.37	12.62	.38	.50	3.87	.07	.39
8589	52.18	29.20	1.11		11.18					

These analyses represent basic labradorite. Both of the analyses are of material from near the northern boundary of the Duluth gabbro, which is practically identical with the gabbro near Gabimichigami Lake.

The plagioclase is frequently so crowded with inclusions that it is dark gray in color, macroscopically, and distinctly gray in thin section, under low powers of the microscope. (Pl. XI-A) These inclusions consist principally of tiny black or dark brown needles and plates which are orderly arranged in lines parallel to differnet crystallographic planes. Such inclusions have been studied in detail by Anderson,** in his work on adventurine feldspars, and he concludes

**Anderson, Olaf, On adventurine feldspars. American Journal of Science, ser. 4, vol. 40, p. 351-399, 1915.

that they are hematite lamellae. He concludes that they have been formed by unmixing of an originally homogeneous solid solution of the feldspar and hematite (or a ferric compound) in such a manner that thin hematite lamellae have separated along structural planes (translation planes) of the feldspar."

Many of the inclusions in the labradorite of the Duluth gabbro have hexagonal outline and closely resemble those figured by Anderson. They are probably hematite. Others are in form of black needles, and are probably rutile or ilmenite. Other inclusions that are often very abundant are extremely long, thin opaque needles. They are so thin that no color can be detected, and they seem to be opaque, and without birefringence. They have a diameter of 0.0001 to 0.001 mm., and a length of 0.001 to about 2 mm., so that the ratio of length to diameter is often as much as 1000. Even the longest needles seem to be perfectly straight.

Other minerals which occur occasionally as inclusions in the plagioclase are apatite, augite, and magnetite.

The plagioclase is usually very fresh, but sometimes shows a little saussuritic alteration.

The augite is the titaniferous variety. It usually has a decided pink tinge, especially in sections slightly thicker than normal. It sometimes shows slight pleochroism, colorless to pink, and has strong dispersion, so that many sections fail to show complete extinction between crossed nicols. It usually shows imperfect cleavage, although sometimes good cleavage is developed. Diallage parting is sometimes noticeable, and is accompanied by the peculiar rows of platy inclusions described and figured by figured by Bayley in the article referred to above (p. 703), and like those described and figured by Judd,* from the peridotites and gabbros of Scotland.

*Judd, J.W., On Tertiary and older peridotites of Scotland. Quart. Jour.Geol. Soc. vol. 41, p. 354-418 1885, Plate XI.

Bayley referred to the secondary nature of these inclusions, and

suggested that they are due to they are due to the decomposition of the pyroxene along solution planes, following a similar suggestion by Judd. As an alternative possibility, it might be suggested that these inclusions have an origin similar to that of the hematite inclusions in feldspar; that is, they may have been formed by an unmixing of an originally homogeneous solid solution of augite and ilmenite (or rutile) in such a manner that the ilmenite separated out along structural plans of the augite.

In addition to the rows of platy inclusions, the augite sometimes contains inclusions in the form of opaque needles which are often arranged in rows parallel to crystallographic planes, and which are sometimes so abundant as to form a densely intersecting network in the augite. (Pl. XI - B) They are probably ilmenite.

Parallel intergrowths of thin plates of augite and hypersthene may someimes be observed.

Olivine is practically always present in the gabbro. It is colorless or slightly yellow in thin section, and is an iron-bearing variety. The following analysis by Hillebrand* is of an

*Bagley, W.S. Basic Massive Rocks of the Lake Superior region. Quoted by Journal of Geology, vol. 1, p. 705, 1893.

olivine from a phase of the gabbro similar to that near Gabimichigami Lake. It is a hyalosiderite, with a Mg:Fe ratio of about1.5::1

SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	CoO	NiO	CaO	MgO	H_2O	Total
35.58	1.22	0.92	tr	33.91	0.35	0.20	?	0.90	26.86	0.31	100.25

The olivine is usually quite fresh, and rarely shows much alteration other than the production of limonite due to weathering. Sometimes it has been slightly serpentinized, but a more common evidence of alteration is the presence of spongy magnetite in

tiny clumps and dendritic masses, which are distributed along cracks in the olivine. These masses are in appearance exactly like those described and figured by Judd*from the olivine in the peridotites of Scotland, and which were regarded by him as due

*Judd, J.W. #OP. cit. p. 381-383, Pl. XII-A, 1-7, 1885.

to the action of solutions penetrating along cracks and solution planes and depositing iron oxides derived from adjacent portions of the crystal.

Hypersthene is sometimes present in small amount. It is very light colored in thin section and has the usual pleocroism in pink and green tints.

Magnetite and brown biotite are always present in small amount, and apatite prisms are not uncommon accessories.

Small amounts of pyrrhotite and chalcopyrite occur in the gabbro at many places. They wore observed by the writer at the following localities:

1. Duluth, Minnesota, at a small quarry east of Lincoln Park.

2. Gabimichigami Lake, at several points along the east shore.

3. Shoofly Lake, southeast of Kekekabic Lake, on the east shore near the north end of the lake, in Sec. 12, T. 64 N., R. 7 W.

4. Round Lake, southeast of Snowbank Lake, on the south shore, in Sec. 7, T. 63 N., R.8 W.

Specimens of the sulphide-bearing gabbro from Gabimichigami Lake were polished and studied under the microscope, following the mineralographic methods described by Murdoch*, and it was

*Murdoch, Joseph, Microscopical determination of the opaque minerals, New York, 1916.

found that pentlandite is frequently present, in addition to the other two sulphides.

Order of Crystallization.

The order of crystallization in the gabbro, as recorded by the minerals now present, was as follows:-

1. Apatite.
2. Magnetite, olivine, and augite in very minor amounts.
3. Labradorite.
4. Most of the olivine.
5. Most of the sugite (and hypersthene).
6. Most of the magnetite.
7. Biotite.
8. Pyrrhotite.
9. Chalcopyrite and pentlandite.
10. Serpentine.

The apatite was undoubtedly an early mineral to crystallize since it is nearly always indiomorphic and is very often completely enclosed by plagioclase or any of the other constituents. But contrary to the usual course of crystallization, the magnetite, olivine, and augite crystallized only in very small amount prior to the separation of the plagioclase and by far the greater portion of these minerals crystallized later than the plagioclase. All three occur for the most part in irregular, often angular or wedge-shaped masses between idiomorphic plagioclase crystals and moulded around them. (Pl. XII-A and B and Pl. XXVI A). The augite was at least in part later than the olivine, since it very frequently occurs in the form of rims around the latter,

either entirely or partially surrounding it, as described by Bayley.*

*Bayley, W.S., Basic massive rocks of the Lake Superior region. Journal of Geol. vol, 1, p. 706, 1893.

However, there is not always to be distinguished sharp periods of crystallization, as there was more or less overlapping of 3 and 4, 3 and 5, and 5 and 6, above. Occasionally the augite and feldspar crystallized simultaneously, resulting in an intergrowth of the two in which tongues of augite extend into the adjacent plagioclase. Such an intergrowth was figured by Bayley,**

**Op. cit. p. 709, fig. 5.

and a similar one is shown in (Pl. XIII-A).

Rarely olivine shows a similar intergrowth, but only one instance was seen in the sections examined. (Pl. XIII-B)

Magnetite and augite sometimes show similar structures which may be due to primary intergrowth. This is a very abnormal feature, however, and is rarely seen. (Pl. XIV-A and B.)

Magnetite is often later then augite and olivine, as well as plagioclase, as it is found surrounding and penetrating them in such a manner as to suggest corrosion of the older mineral and partial replacement by the magnetite. (Pl. XVIII-A).

Biotite occurs very largely as rims around magnetite, or as plates with a core of magnetite, and is particularly common where magnetite and feldspar are in contact. (Pl. XV-B) It seems to be what Sederholm*** calls a "synantectic mineral". It occurs also on the contact of augite and plagioclase, and olivine and plagioclase. It is probably post-magmatic or late magmatic

***Sederholm, J. J., On synantectic minerals. Com. Geol. Finland, No. 48, 1916.

in origin, due perhaps in some cases to reaction between magnetite or a ferro-magnesian silicate ~~with~~ and the plagioclase in contact with it, and in others to the pneumatolytic action of magmatic gases. When thin plates or blades of biotite are found cutting across plagioclase crystals and penetrating olivine, or cutting the contact of plagioclase and olivine or augite at a sharp angle they cannot well be explained by any other hypothesis than that of pneumatolysis. (Pl. XV-A).

Occurrence of Sulphides.

The sulphides occur in small grains with irregular, rounded or angular outlines cutting or embaying any of the silicates and magnetite. They are most abundant in labradorite, and long, slender grains or rows of angular grains penetrate it along cleavage planes. (Pl. XVI A and B). Frequently individual grains are connected by narrow stringers of the sulphides. These grains consist of a single sulphide, or of an intergrowth of pyrrhotite and chalcopyrite, or of all three. The chalcopyrite is always definitely younger than the pyrrhotite, and cuts it in narrow veinlets. (Pl. XVII-A). The pentlandite is always intimately associated with the chalcopyrite, and the two form parallel intergrowths of narrow bands or narrow wedge-shaped masses. Sometimes chalcopyrite appears to be cutting or penetrating the pentlandite grains, and vice versa. They are probably of about the same period of formation.

These sulphides are believed by the writer to be of magmatic origin, and to belong to a late stage in the solidification of the gabbro itself. They were deposited before the form-

ation of serpentine, since serpentine-filled cracks traverse chalcopyrite grains. The sulphides were deposited before the dynamic metamorphism which caused the straining and fracturing of the feldspar, since serpentine-filled cracks which traverse grains of chalcopyrite also cut across strained feldspar grains whose twinning lamellae are offset on opposite sides of the cracks.

Insofar as mode of origin is concerned, these sulphides are to be classed with the magmatic sulphide ores, and they have many characteristics in common with those summarized by Tolman and Rogers*

*Tolman, C.F. Jr., and Rogers, A.F., A study of the magmatic sulfid ores, Leland Stanford Junior University Publications, University series, p.70, 1916.

Corona-like Intergrowths of Plagioclase and Pyroxene.

Many sections of the gabbro contain fine intergrowths of two minerals which form narrow rims around olivine and resemble the coronas, or reaction rims which in many rocks surround that mineral where it is in contact with plagioclase. The intergrowth consists of slender, vermicular rods of a colorless, highly refracting mineral lying in a matrix of plagioclase. The highly refracting mineral has an index of refraction which is about the same as that of the augite in the gabbro, and although the rods are not large enough for accurate determination it is probably augite. Bayley, who studied this feature of the gabbro in 1892,* considered it augite,

*Bayley, W. S., A fibrous intergrowth of augite and plagioclase, resembling a reaction rim, in a Minnesota gabbro, Amer. Jour. Sci. 3d, series, vol. 43, p. 250, 1892.

principally because "the augite of the rock frequently sends out prolongations of its own substance into the surrounding plagioclase, and the ends of these prolongations have characteristics that are identical with those of the more highly refractive component of the intergrowths." The plagioclase of the intergrowth has a higher index of refraction than the labradorite of the gabbro, and is probably a more basic plagioclase, perhaps about $Ab_{35}An_{65}$. In a few instances the writer found the plagioclase of the intergrowth with albite twinning lamellae large enough that the extinction could be measured, and the extinction was that of a basic labradorite. The composition probably varies a little, however, as a single grain of plagioclase sometimes shows wavy extinction. The plagioclase of the intergrowth is never optically continuous with the adjacent labradorite, and it is usually made up of several grains with different optical orientation, rather

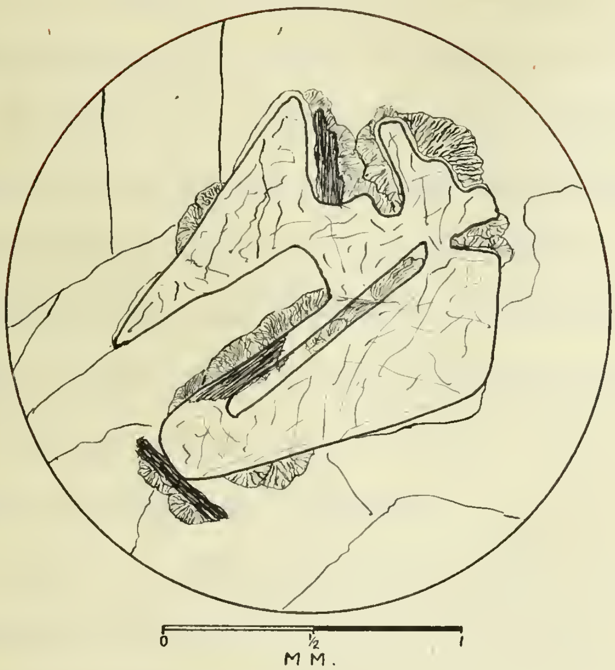
than of a single grain.

The intergrowth is most abundant at the contact of olivine and plagioclase, but also occurs between biotite and plagioclase, (Pls. XVII B and XVIIIA) and rarely between augite and plagioclase, It may form a rim around the olivine, or occur in small clumps at points along the contact of the olivine and plagioclase. In such clumps, and frequently in the large rims, the rods of augite have a divergent arrangement, and always diverge toward the plagioclase. The intergrowth has a rounded or wave-like front which is convex toward the plagioclase, never toward the olivine, and which is always invasive in the plagioclase. (Fig. 1). The olivine, in this rock was formed for the most part later than the feldspar, and surrounds and encloses idiomorphic crystals of labradorite, Where the intergrowth lies on the contact of olivine with such crystals of labradorite, there can be no doubt that it has actually replaced the feldspar. Sometimes only the centers of such crystals remain unreplaced, and have curved, corroded outlines, while the fibrous intergrowth fills out the shape of the original crystal. (Pl. XVIII B and Fig. 1.) In such cases the inclusions in the original labradorite crystal frequently extend unchanged in abundance or in direction into the intergrowth. (Pl. XIX-A). All gradations could be traced in a single section from fresh prisms of labradorite enclosed by olivine to others which consist entirely of the intergrowth, but which still have the outlines of idiomorphic labradorite crystals. There is never the slightest suggestion of any invasion or replacement of olivine by the intergrowth.

Bayley, who studied this intergrowth in 1892*, interprets

*Bayley, W.S., op. cit. p. 520.

Figure 1.



Corona-like intergrowths of plagioclase and augite.

A single grain of olivine partially or completely encloses laths of plagioclase which are more or less completely replaced by the intergrowth. The intergrowth also occurs at the contact between biotite and plagioclase in the upper portion of the figure, near the center, and in the lower left-hand portion. Narrow rims of augite surround the olivine along the upper border, and along the lower right-hand border.

its origin as follows:

"We may safely infer, therefore, that the fibrous intergrowth, which so closely resembles a reaction rim between olivine and plagioclase, but which is surely not such, is merely a granophyric aggregate of plagioclase and pyroxene. The major portion of the latter mineral in the rock separated before the feldspar, and taking advantage of the surfaces afforded by the already formed olivine and magnetite, fastened upon them. But in many cases, before the crystallization of the pyroxene had ceased, the feldspar began to form, and the two minerals crystallized together micropegmatitically."

Such a mode of origin does not agree with all of the features of the intergrowth, however. It is true that the augite in the gabbro sometimes forms intergrowths with the labradorite, but in such cases the intergrowth is obviously primary, the augite tongues are connected and optically continuous with a large grain of augite, and the feldspar of the intergrowth is a labradorite optically continuous with a large labradorite grain nearby. Such primary intergrowths do not have an intrusive relation to the labradorite. The corona-like intergrowth, on the other hand, replaces feldspar which crystallized in idiomorphic prisms before the crystallization of the augite or olivine. The fact that the inclusions in the intergrowth lie parallel to those of the surrounding labradorite, regardless of the orientation of the feldspar of the intergrowth, indicates that the intergrowth has replaced the labradorite without disturbing its original inclusions. (Pl. XIX-A)

Sederholm* has reviewed the literature dealing with such

*Sederholm, J.J., On synantectic minerals, Bull. Comm. Geol. de Finlande, Bull. 48, pp. 9-47, 1916.

intergrowths, and described some observations of his own. He favors the theory that the intergrowths are of a secondary nature and formed by metamorphic agencies later than the solidification of the rock. He emphasizes the fact that they are entirely absent in gabbros and diabases which have undergone no later metamorphism, while they are common in old basic rocks which have been metamorphosed. As to the process by which they were formed, he stated, "The process by which the coronites have originated has not consisted exclusively in a reaction between the adjacent minerals. These minerals have supplied only a part of the constituents of the coronas, while another part has been transported in solution from more distant places of the same rock masses." (p.41)

In the writer's belief the evidence is conclusive that the corona-like intergrowths in the Duluth gabbro are replacements of plagioclase, and that the replacement took place after main period of solidification of the rock. The evidence is not conclusive, however, as to whether the process was a phase of the last stages of crystallization of the magma, or whether it was a metamorphic process which took place after the rock was completely solidified. The fact that the gabbro shows many metamorphic features indicates that a metamorphic origin for the intergrowth is possible. (See p. 111).

Local phases of the gabbro.

There are local variations in texture, and in relative abundance of the different constituents, so that the following phases were recognized in the immediate vicinity of Gabimichi-

gami Lake:

a. Normal coarse-grained olivine gabbro.

b. Hyperite.

c. Norite.

d. Coarse-grained ophitic gabbro (gabbro pegmatite)

e. Fine-grained granulitic gabbro.

f. Fine-grained ophitic gabbro.

Normal coarse-grained olivine gabbro.

Bayley* states that "the normal rock of the great gabbro is so uniform in its general character that, after studying

*Bayley, W.S. Basic massive rocks of the Lake Superior region. Journal of Geology, vol. 1, p. 698, 1893.

carefully one of its hand specimens, others might easily be identified among a collection of specimens of the basic rocks of the Lake Superior region, without much danger of error." This "normal rock" is a coarse-grained gabbro, usually olivinitic, with variable proportions of labradorite, augite, and olivine, principally, and minor amounts of hypersthene, biotite, and magnetite. A geometric analysis of the mineral composition of one section (343) gave the following proportions by volume, and the specific gravity noted. Other sections show slightly different proportions, but the general features are very uniform.

Labradorite-------	69.9	Specific gravity------ 2.97
Augite------------	11.8	Johannsen's Family No. 2315
Olivine-----------	11.0	
Biotite-----------	4.2	(higher than normal)
Hypersthene-------	2.2	
Magnetite---------	0.9	
	100.0	

The position which this rock occupies in Johannsen's quantitative mineralogical classification* was computed and its family number is indicated in the above table.

*Johannsen, Albert, Suggestions for a quantitative mineralogical classification of igneous rocks, Jour. Geol. vol. 25, pp.63-97,1917

Hyperite.

Locally the ferromagnesian minerals increase in abundance, and the gabbro grades into a rock with the mineral composition of a hyperite. A geometric analysis of this rock gave the following composition by volume:

Labradorite-----	49.6
Olivine---------	24.8
Augite----------	12.2
Hypersthene-----	9.8
Magnetite-------	3.2
Biotite---------	0.4
	100.0

Specific gravity---- 3.22

Johannsen's Family No. 3315

This rock is lighter in color than most of the gabbro, and is brown on fresh fracture owing to the presence of the brown hypersthene.

Norite.

As another variation of the gabbro the augite decreases in amount and the hypersthene becomes locally abundant until the rock is more properly a norite. This phase was observed as a border phase of the main mass of the gabbro where it approaches the area of Ely greenstone at the southwest corner of the Lake. It becomes finer-grained toward the border of the mass, with

plagioclase grains a millimeter or less in diameter, but does not show the granulitic texture exhibited by some of the other fine-grained border phases. The texture is usually distinctly ophitic.

In the five sections of this rock which were studied no olivine was found and only a small amount of augite. Hypersthene makes up 40 or 50 per cent of the rock, with about 5 per cent of magnetite, 3 or 4 per cent of brown biotite, and the remainder plagioclase.

The placioclase averages about labradorite ($Ab_{40}An_{60}$), but it is often zoned with about $Ab_{25}An_{75}$ in the center and about $Ab_{45}An_{55}$ on the border of the crystals. The tiny inclusions so common to the plagioclase of most of the gabbro becomes less abundant as the rock becomes finer-grained toward the border of the mass. The plagioclase grains are often fractured and show strain shadows, which are probably the result of movements in the mass before complete solidification and during the final cooling.

The hypersthene is deeper in color and more strongly pleochroic than most of the hypersthene which occurs in small amount in the coarse gabbro. It is frequently altered more or less completely to a grayish-green, fibrous serpentine (bastite), the fibers penetrating along cracks and cleavage planes. Accompanying the serpentine is frequently a pale green hornblende in fibrous masses.

The augite is a very minor constituent. When present it is usually much altered to a fibrous, pale green hornblende.

The biotite frequently occurs as large poikilitic plates enclosing indiscriminately grains of all of the other constituents. These plates have probably developed subsequent to or as the result of the metamorphism which produced the strained feldspars and the altered hypersthene, since fresh biotite showing no signs of bent or twisted lamellae encloses grains of greatly altered hypersthene and of fractured and strained plagioclase. Small flakes of biotite are also frequently intergrown with the hornblende and serpentine resulting from the alteration of the hypersthene.

An unusual constituent which was observed in one section, is zircon in small grains associated with quartz. Both of these minerals are evidently due to absorption of material from the rock intruded by the gabbro, and are probably derived from fragments of quartzite which were included in the gabbro at the time of its intrusion. The section in which they were observed was cut from a specimen taken from the edge of the gabbro mass within a few feet of its contact with a metamorphosed quartzite in which zircon is a common accessory.

Away from the border the norite becomes coarser grained, and locally becomes much richer in plagioclase. Where it is exposed on the islet in the southwest corner of the lake it is coarse - grained, light gray in color, and at first glance appears to consistalmost entirely of plagioclase in large tabular crystals about 0.5 cm. thick and 1 to 2 cm. in diameter. Close inspection shows, however, that between the plagioclase grains lie wedge-shaped masses of a fibrous, greenish-gray mineral, with which is

associated a little brown biotite. In thin section this material may be recognized as an intergrowth of anthophyllite and actinolite, with a little calcite and a few flakes of brown biotite. The anthophyllite is colorless to brownish or greenish gray, and the actinolite is slightly pleochroic in pale green to bluish green tints. The plagioclase is a basic labradorite, $Ab_{35}An_{65}$, and is so crowded with tiny inclusions of hematite and ilmenite that it is decidedly gray in thin section. It is very much altered to a saussuritic aggregate of secondary minerals.

No trace was left in the section examined of the original pyroxene from which the amphiboles were probably derived. A.N. Winchell* states that cordierite norites are common along the

*Winchell, A.N. Gabbroid rocks of Minnesota, Amer. Geol. vol. 26 p. 295, 1900.

northern edge of the Duluth gabbro at several localities, including Gabimichigami Lake. No such rocks were found by the writer. The only cordierite-hypersthene rocks found were a part of the Gunflint iron formation.

At two localities along the shores of Gabimichigami Lake an extremely coarse-grained phase of the gabbro was observed, which might almost be called a gabbro-pegmatite. The same sort of thing may be found at many places in the gabbro, and particularly good examples were seen by the writer exposed in the rail road cuts a few miles southwest of Duluth. At the latter locality the pegmatite forms well-defined dikes cutting the gabbro, but in many cases, as at the localities on Gabimichigami Lake, the pegmatite occurs in very irregular stringers and lenslike masses which grade into normal gabbro on either side.

At the latter localities the weathered surface of the pegmatite is covered with a coating of green chrysocolla due to the weathering of chalcopyrite, which is disseminated in small grains through the gabbro.

The pegmatite consists of the same minerals usually occurring in the gabbro, with the addition of chalcopyrite and pyrrhotite and a little pentlandite. The plagioclase is a labradorite, about $Ab_{45}An_{55}$, and the augite the usual pink variety. Crystals as large as 15 centimeters long were found of both plagioclase and augite. Yellowish olivine occurs in granular masses between the plagioclase laths and included in augite crystals. Sometimes olivine and magnetite are intergrown in parallel masses suggesting simultaneous intergrowth. Magnetite occurs later than the plagioclase, augite or olivine, in wedge-shaped masses between these minerals, and again it occurs in intimate intergrowth with augite as if it crystallized simultaneously with it. Hypersthene is sometimes present either in wedge-shaped grains between the plagioclase laths or in parallel intergrowth with augite. Biotite is common, but not abundant. It usually is found surrounding magnetite. Apatite is a common accessory in idiomorphic prisms.

The texture is ophitic in that the plagioclase crystallized first in long prisms, and the other minerals crystallized later and lie in wedge-shaped masses between the plagioclase laths. Finer-grained portions of the rock show this feature well in thin section.

A peculiar feature of this rock is the frequent development of corona-like intergrowth of plagioclase and pyroxene

which occurs around olivine grains where they come in contact with plagioclase. It is described elsewhere (p. 46).

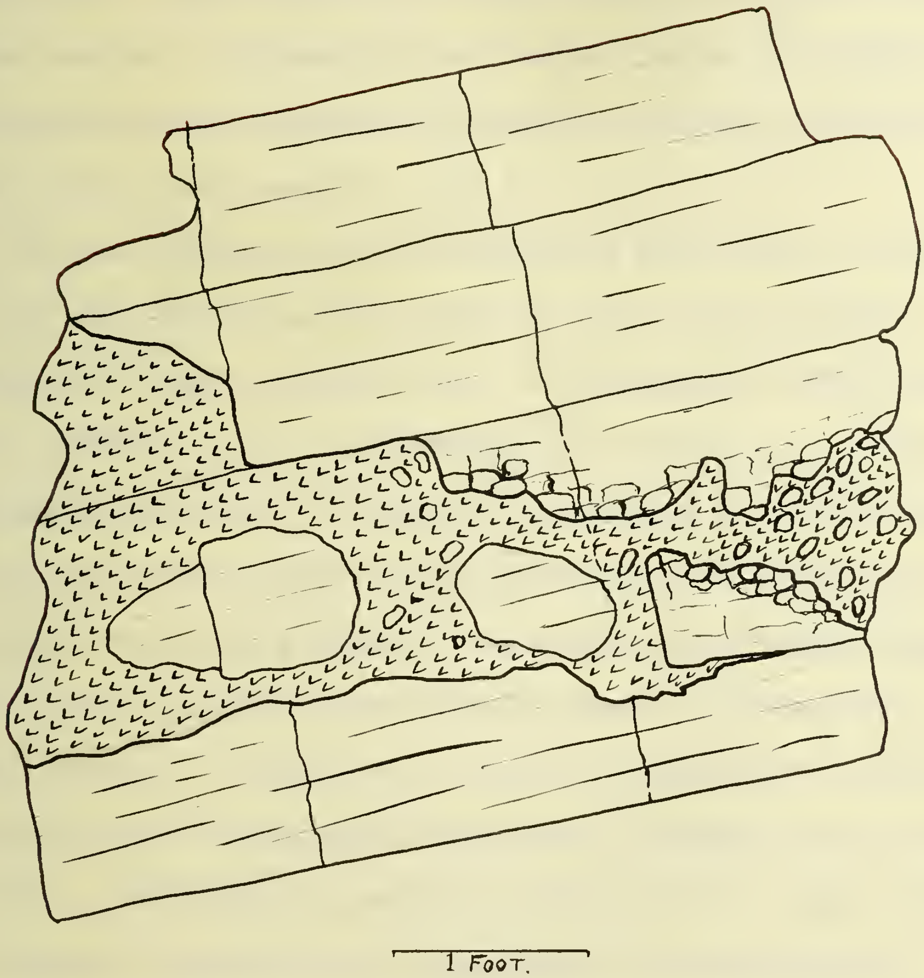
Fine-grained granulitic gabbro.

At one locality on Gabimichigami Lake (on the south side of the large island in the NW $\frac{1}{4}$ of Sec.6, T. 64 N. R. 5 W. there is a massive, fine-grained, dark gray rock which is intruded by the normal, coarse-grained gabbro in a very irregular manner. This fine-grained rock at first glance looks very much like some of the metamorphosed quartzites, and was so interpreted by early observers.* The rock is jointed with joint planes very nearly horizontal and vertical, and on weathered surfaces an appearance very much like that of bedding is produced, which heightens the resemblance to the metamorphosed quartzites or graywackes. This jointing was, however, produced after the intrusion of the gabbro, and the joint planes extend across the contact of the two rocks.

*Winchell, Alexander, Minnesota Geol. & Nat. Hist. Survey, 15th Ann. Rept. p. 171, 1887.

The contact between the two is very irregular. The gabbro sends small tongues into the fine-grained rock, penetrating it in a most intricate manner. (Fig. 2). These tongues are crowded with fragments of the fine-grained rock, and these inclusions are abundant in the gabbro for a distance of 40 or 50 feet from the contact. They vary in size from those only a centimeter or a few centimeters in diameter to large boulders a meter or more across. Most of the inclusions are well rounded, and must have been friable at the time they were picked up by the gabbro. There is no sign of chilling of the gabbro along the contact or

Figure 2.



A stringer of coarse-grained gabbro cutting through fine-grained granulitic gabbro, and containing many inclusions of the granulitic gabbro. (From a sketch made in the field.)

in the narrow apophyses which penetrate the intruded rock. It is quite as coarse-grained on the contact as in the interior of the gabbro mass. The contact is fairly sharp, and in a single thin section one may see portions of large grains of plagioclase or augite penetrating between the smaller grains of the fine-grained rock along an irregular line.

In thin section the fine-grained rock may be seen to contain the same minerals that make up the coarse gabbro, but in somewhat different proportions. It contains a relatively greater amount of the ferro-magnesian minerals, and has a higher specific gravity. Its specific gravity is 3.00-3.10, while that of the coarse gabbro is 2.76-2.94. The minerals present are labradorite, pink augite, hypersthene, olivine, magnetite, biotite, and a little brown hornblende. The rock is a fine-grained gabbro. It generally shows a granulitic texture, with all constituents allotriomorphic, well rounded, and of about the same size. The size of grain is about 0.5 to 1 mm. Occasionally, augite, hypersthene, or olivine is developed in large poikilitic crystals.

Bayley* has described in detail such fine-grained rocks from

*Bayley, W.S., Basic massive rocks of the Lake Superior region. Journal of Geology, vol. 3, pp. 1-20, 1895.

the Akeley Lake and other regions in northeastern Minnesota, and he distinguishes several mineralogic varieties, including an olivinitic, a hypersthenic, a diallagic, a biotitic and hornblendic, and non-feldspathic varieties. He calls them granulitic gabbros, using the term applied by Judd to similar rocks from Scotland.*

*Judd, J. W. On the gabbros, dolerites and basalts of Tertiary age. Quart. Jour. Geol. Soc. vol. 42, p. 49, 1886.

The fine-grained gabbro on Gabimichigami Lake is a granulitic gabbro ahowing mineralogical variations similar to those described by Bayley. Of eleven sections cut from different portions of the massive rock and the inclusions in the coarse gabbro, no two are exactly alike, and a great variation in mineral composition is shown.

The commonest variety is an olivine gabbro with plagioclase (labradorite) about equal to the ferromagnesian minerals, of which augite is the most abundant. The sum of the hypersthene, olivine and magnetite is usually less than the total augite, and the texture is generally uniformly granulitic. Occasionally several of the pyroxene grains are optically continuous and form parts of a single large poikilitic crystal.

Another variety contains abundant hypersthene as the characteristic ferromagnesian mineral, with smaller amounts of augite, olivine, and magnetite, in addition to the plagioclase. In this variety the hypersthene occurs for the most part in the form of large poikilitic crystals enclosing rounded grains of plagioclase, augite and magnetite. A geometric analysis of this phase showed the following proportions by volume:

Labradorite ---------	46.8	
Hypersthene ---------	33.2	Johannsen's Family No. = 3315
Augite --------------	9.5	
Olivine -------------	5.4	
Magnetite -----------	3.2	
Biotite -------------	1.9	
	100.0	

Another variety contains about 80 per cent of augite, which occurs principally in the form of aggregates of irregularly intergrown grains surrounded by smaller rounded grains of labradorite, augite, olivine and magnetite. In this rock the plagioclase sometimes forms large poikilitic crystals enclosing rounded grains of the other minerals.

In another variety a greenish-brown hornblende appears in considerable abundance, although subordinate in amount to the augite. The hornblende is at least in part an alteration product of the augite.

A somewhat different variety was observed at one point. It occurs in a mass several yards across, which was poorly exposed and whose relation to the coarse gabbro could not be certainly determined. It seems to be a large block of the granulitic gabbro which was engulfed in the coarse gabbro at the time of its intrusion. It contains the same minerals found in the other varieties, but the texture is the most completely granulitic noted in any of them. Not only are all of the constituents well rounded, but they are all somewhat elongated, even to the magnetite, and there is a parallel arrangement of the greatest and least dimensions of the elongated grains. (Pl. XX A and B) This variety is also more feldspathic than any of the others. The constituents are in the following proportions by volume:-

Labradorite ----------	67.7
Augite ---------------	15.7
Hypersthene ----------	3.8
Olivine --------------	5.6
Magnetite ------------	7.2
	100.0

Johannsen's Family No.= 2315

The granulitic texture as first applied to this type of gabbro by Judd* was explained as due to the crystallization of a

* Judd, J. W., On the gabbros, dolerites and basalts of Tertiary age, Quart. Jour. Geol. Soc. vol. 42, p. 49, 1886.

moving magma in which the grains as they formed were rolled around and prevented from interlocking freely. The fine-grained granulitic border phase of the Duluth gabbro probably crystallized under some such conditions. The fact that there are definite intrusive relations between this phase and the normal coarse-grained gabbro shows that the intrusion was not a simple process, the result of a single impulse, but that it must have been the result of successive intrusions. The first intrusion must have been small in amount since it cooled rapidly enough to produce a fine-grained rock. It was also of material higher in iron and magnesia than the great mass of material which was later intruded. This indicated by the predominance of ferromagnesian minerals, and is substantiated by the few analyses which have been made. Bayley** gives an analysis by N. H. Stokes of a granulitic

** Bayley, W. S., Basic massive rocks of the Lake Superior region Journal of Geology, vol. 3, p. 10, 1895

hypersthene gabbro which he says is very rich in hypersthene and biotite and poor in feldspar. (No. 7036) In another place***

*** op. cit. vol. 1, p. 712.

he gives an analysis, also by Dr. Stokes, of a coarse gabbro which he says " is more nearly of the average composition of the entire mass" (No. 8786)

	7036	8786
SiO_2	46.96	46.45
TiO_2	0.62	1.19
Al_2O_3	14.13	21.30
Cr_2O_3	tr.	
Fe_2O_3	0.76	0.81
FeO	14.95	9.57
NiO	0.06	0.04
MnO	0.93	tr.
CaO	2.32	9.83
MgO	15.97	7.90
K_2O	1.68	0.34
Na_2O	0.35	2.14
H_2O at 105°	0.07	0.14
H_2O above 105°	1.26	1.02
P_2O_5	0.03	0.02
	100.09	100.75

The hypersthene gabbro (7036) has a very high iron and magnesia content, and low alumina, calcium, and soda, as is to be expected from the low feldspar content.

Where the granulitic gabbro was subject to movement during the period of crystallization, the granulitic texture resulted. In some portions of the mass, however, movements must have ceased while a portion of the magma was still liquid, and the remaining portion crystallized under static conditions to form the large poikilitic pyroxene, olivine and feldspar grains. While the granulitic gabbro was still hot, large amounts of new material were introduced which intruded that already solidified, forcing

itself into fractures and breaking off fragments which became engulfed in the intrusive. The new material was in sufficient quantity and at such a temperature that it was permitted to crystallize slowly and develop a coarse-grained rock.

The mass which was described as a large block of granulitic gabbro engulfed in the magma, has such a completely granulitic texture that it must have a complicated history. It is probable that after it was engulfed in the magma it was recrystallized under great pressure; and the grain tended to elongate in the direction at right angles to the greatest pressure. Simple movements in a solidifying magma such as postulated by Judd could hardly explain such a parallel arrangement of elongated grains. (Pl XX-A and B).

Fine-grained ophitic gabbro in outliers.

In spite of its enormous extent, the Duluth gabbro contains few apophyses extending out into the surrounding rocks. Clements* refers to two outliers of the gabbro which are believed to be offshoots of the gabbro, although no connection between the two can be traced. One of these outliers is about three-quarters of a mile north of the northern boundary of the gabbro, just north of Gabimichigami Lake in secs. 29 and 30, T. 65 N., R. 5 W. This outlier is about 1/3 mile in diameter, as mapped by the U. S. Geological Survey, and along its eastern edge it certainly cuts across the bedding of the conglomerates and slates with which it comes in contact.

*Clements, J. Morgan, The Vermilion iron-bearing district, Minnesota. Mono. 45, U. S. G. S. p. 398, 1903.

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The rock in this outlier is a medium-to coarse-grained gabbro which is very similar in appearance to the normal coarse-grained gabbro, except that the texture is more distinctly ophitic. In the center of the outlier the rock is almost as coarse-grained as the normal gabbro, but along its border it is finer-grained, the length of plagioclase prisms decreasing from about o.6 cm in the former to about 0.4 cm in the border rock.

Petrographically the rock of the outlier is identical with the normal gabbro. The plagioclase is the same--- a labradorite about $Ab_{35-40}An_{65-60}$-----the augite is the same pink, slightly pleochroic variety, and the other constituents are the same as far as can be determined. Even the relative proportions of the minerals are about the same. The one section which was measured showed the following proportions by volume:-

Labradorite-----	63.8	
Augite----------	21.2	
Olivine---------	4.8	
Magnetite-------	3.6	Johannsen's Family No. 2315.
Biotite---------	2.6	
Apatite---------	0.1	
Hornblende------	2.1	(secondary to augite)
Chlorite--------	1.7	(secondary to biotite)
Calcite---------	0.1	
	100.0	

LOGAN SILLS.

Along the southeast shore of Gabimichigami Lake is another small mass of gabbro which has no visible connection with the

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main mass about 1/4 mile east and south. This mass is probably a sill of the same nature as the Logan Sills which are more abundant farther east. It may be the same sill referred to by Clements,* although this sill is on the east shore at the southeast corner of the main lake, while he states that "The first exposure of such a sill was noticed on the southeast side of Gobbemichigamma Lake, but this cannot be traced far."

*Clements, J. M.? The Vermilion iron-bearing district, Minnesota, Mono. 45, U. S. Geol. Survey, p. 398, 1903.

It is possible that the above is a misprint and that Clements referred to the sill on the southeast side of the lake. No such mass was found by the writer on the southwest side of the lake.

The sill was found on the little point of land which forms the east shore of "The Narrows", as Winchell called it, through which one enters the south bay of the lake. This is near the N. E. cor. of the S$_x$ W. $\frac{1}{4}$ sec. 1, T. 64 N., R. 6 W. A medium-grained, dark brown ophitic gabbro outcrops at one point at the water's edge on the north side of the point, and scattered outcrops are found on up the hill to the south. To the east the rocks are covered by loose, weathered material. At the west end of the point a vertical cliff of metamorphosed Gunflint iron-formation overlooks the water, and above that the hill rises to a height of about a hundred feet above the level of the lake. The very top of thehill is capped by a mass of black, glistening rock which consists principally of black hornblende with a few indistinct patches of light-gray minerals. This rock grades downward to the south, east and northeast into a dark brownish-

gray, medium- to fine-grained gabbro. The mass is probably a sill, and has a low dip (20°-30°) toward the east or a little south of east.

Medium-grained rock.

The lower part of the sill consists of a medium-grained gabbro with a texture which might be said to be intermediate between the ophitic and granulitic. Macroscopically the rock appears ophitic, and is dark brown to black. Under the microscope the texture differs from the normal ophitic in that the plagioclase laths have somewhat rounded contours, and the augite and olivine grains between the feldspar are in large part masses of rounded grains, instead of angular and wedge-shaped masses.

The minerals are the same as in the normal gabbro, with the addition of brown hornblende. The plagioclase averages about labradorite, but is often zoned from about $Ab_{35}An_{65}$ in the center to about $Ab_{55}An_{45}$ on the outside. The center of the grains are usually crowded with inclusions, while the outer zone is relatively free from them. These inclusions are of three kinds:

a. The rows of tiny hematite and ilmenite plates so common in the normal gabbro.

b. Numerous colorless prisms and rods with high refraction and low double refraction, showing all gradations from sub-microscopic spots to crystals 0.2mm or more in diameter and twice as much in length. The larger crystals are readily recognized as apatite, and the smaller ones are probably the same mineral. Many of even the smaller crystals show a hexagonal outline, and where the extinction is not obscured by that of the feldspar it

is parallel.

c. Brown to greenish-brown pleochroic plates showing strong absorption. They are sometimes as large as .05mm in diameter and can be recognized as biotite in some cases and hornblende in others.

The augite is the same slightly pleochroic, pink or pale green variety found in the normal gabbro. It crystallized later than the feldspar and is moulded around plagioclase. It frequently encloses magnetite grains and contains inclusions of brown biotite in rounded flakes, and of tiny crystals of brown hornblende. In addition to these it is sometimes filled with a network of tiny black needles and rounded grains in lines intersecting at angles of 50° to 74°, usually about 70°. (Pl XIX-B) These needles seem to be ilmenite, although no chemical analysis is available.

The olivine also shows angular forms between and around plagiolase grains. It is slightly yellow in thin section, and is probably the same high iron variety (hyalosiderite) found in the normal gabbro. It sometimes encloses rounded grains of magnetite, flakes of biotite, and little crystals of brown hornblende.

A few hypidiomorphic grains of brown hornblende are scattered through the rock, which are probably primary and not derived from the alteration of augite. Although sometimes closely associated with augite and intergrown with it, they show sharp boundaries toward each other, and there is no zonal arrangement or other evidence of an alteration of one to the other. A small amount of bright-green hornblende is secondary to the brown variety.

The crystallization of the rock, as it is recorded by the minerals now present, seems to have begun with the separation of

magnetite and perhaps small hornblende crystals, followed by the crystallization of the plagioclase, together with the minerals which now form the inclusions in it. Augite and olivine crystallized during the same period and for the most part later than the feldspar. Hornblende shows no definite age relation to the other minerals, and seems to have crystallized at any period, whenever conditions were favorable for its formation. It sometimes forms idiomorphic crystals enclosed by feldspar, and again is intergrown with augite which is definitely younger than feldspar. At a late period in the final stages of crystallization biotite was formed, probably by what Sederholm* calls

*Sederholm, J. J. On synantectic minerals Bull. Comm. Geol. de Finlande, No. 48, p. 4, 1916.

"Autometamorphic" processes. (See p. 113.)

A geometric analysis of this rock gave the following proportions by volume:-

Labradorite ---------	59.8
Augite --------------	25.2
Magnetite -----------	6.0
Olivine -------------	4.1
Hornblende ----------	2.6
Biotite -------------	2.1
Apatite -------------	0.2
	100.0

Johannsen's Family No.= 2315

Specific gravity ---- 3.19

Fine-grained basal phase.

This medium-grained rock grades downward into a fine-grained ophitic gabbro at the base of the sill which contains the same minerals, but in slightly different proportions. There is

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more magnetite and augite, and a little more hornblende in the fine-grained rock and almost no olivine. There is also a change in texture, which may, however, be local. A specimen of the fine-grained rock taken from a point about 10 feet from the base of the sill showed a texture which is intermediate between the normal ophitic and the granulitic. The plagioclase crystals are lath-shaped, but the laths are rounded. The augite and olivine lie between the laths of plagioclase, but do not have angular outlines. They consist of groups of grains of different sizes lying in rounded masses between the plagioclase. The magnetite, which is very abundant in this phase (one section contained 12.9 per cent by volume), is also present in rounded, oval, or amoeba-shaped grains. Biotite flakes have their usual form, being most abundant around magnetite grains.

The rounded outlines of the constituents suggests that, like the granulitic gabbro, this rock had only partially crystallized when further movement of the magma took place, preventing the close interlocking of the minerals and the formation of sharp angles, and resulting in somewhat rounded forms. This was not sufficient, however, to completely destroy the ophitic structure previously developed.

Intermediate hornblendic phase.

The gabbro grades upward to intermediate rocks which are very dark and contain variable amounts of the hornblende, to the presence of which the dark color is due. With the increase in specific gravity. Values of 3.18-3.19 were obtained for the gabbro, 3.23, 3.25 and 3.26 for the intermediate rocks, and of

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3.31-3.32 for the black hornblende rock.

In thin section the intermediate rocks have many characters in common with the gabbro into which they grade. The plagioclase is the same, and contains the same apatite and hornblende inclusions, but the rows of little hematite and ilmenite plates and rods are lacking. The apatite and hornblende inclusions are on the whole much larger than in the gabbro, and they nearly always show well-developed idiomorphic outlines.

The augite is the same as in the gabbro, and with the same inclusions. The network of ilmenite rods is present in nearly every grain of augite, and each grain is likewise intergrown with hornblende. Here again the hornblende does not seem to be an alteration product of augite. It is the same dark brown variety that occurs abundantly in idiomorphic crystals elsewhere in the section. It occurs in little irregular isolated patches throughout the augite crystal, but these isolated patches are optically continuous, and are often continuous optically also with a large hornblende crystal alongside the augite. (Pl. XXI A) Moreover the intergrowth is always parallel. Sections cut nearly perpendicular to (001) in the augite not only show excellent basal cleavage of that mineral, but the irregular patches of hornblende also show excellent hornblende basal cleavage (56 degrees-124 degrees). In sections of augite which are nearly perpendicular to (010) the patches of hornblende intergrown with it are also cut nearly perpendicular to (010).

The olivine is the same as in the gabbro, and contains the same inclusions of hornblende, and frequently encloses grains of feldspar.

Magnetite is in much smaller amount and is present as small rounded grains. Biotite is present in small amount.

No trace remains of the ophitic texture. All of the constituents except hornblende are present in rounded grains, while the hornblende grains have idiomorphic or hypidiomorphic outlines for the most part.

Hornblende Peridotite

The black hornblende rock, into which the other grades, is a heavy, jet-black, granular rock with a glistening appearance due to the reflection of light from the cleavage plates of hornblende. A few areas of light-colored minerals sometimes gives it a mottled appearance.

In thin section it is like the intermediate rocks described above, except that it has a much greater abundance of dark brown hornblende. (Pl. XXI B) This hornblende is a brown variety with the extinction of common hornblende. ($Z/c=21°$ max.) It is always brown without the slighest tinge of green. It has very strong absorption and is strongly pleochroic. X=light yellow; Y=light brown; Z= deep brown. It is sometimes twinned. It is usually quite fresh, but is sometimes slightly altered to a bright green hornblende.

The other minerals present are augite, feldspar, olivine, biotite and magnetite. The augite is the same variety found in in the gabbro, but in this rock it does not contain the needles and rods of ilmenite. It sometimes contains rounded hornblende inclusions, and is frequently developed in large skeleton or poikilitic crystals enclosing rounded grains of hornblende, plag-

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ioclase, or biotite. The plagioclase is labradorite, and occurs only in small amount and as small rounded grains between or enclosed in the other minerals. The olivine is the same slightly yellow variety and occurs in irregular rounded grains enclosing grains of hornblende, feldspar, or biotite, or in large poikilitic masses enclosing small rounded grains of these minerals. Biotite is present in small amount as small rectangular or even rounded flakes enclosed in other minerals, or as long slender blades cutting across any of the other minerals. Magnetite is a rare constituent in this rock. A few small rounded grains were found in one section.

The following proportions were determined:

Hornblende -------	71.5	
Augite -----------	14.8	
Labradorite ------	7.0	Johannsen's Family No.= 3315
Olivine ----------	4.5	
Biotite ----------	2.2	
	100.0	

Specific gravity 3.32

The relative proportions of augite and olivine vary, however. In one section augite was practically absent, while olivine made up about 15 per cent of the section.

This rock is evedently closely related to the gabbro, and mineralogically it is a gabbro in which most of the feldspar has disappeared and its place has been taken by hornblende. The great preponderance of hornblende would almost place it with the hornblendites but it seems to be more closely related to Rosen-

busch's* hornblende peridotites. Its close relation to the

*Rosenbusch, Micr. Phys. der Min. u. Gesteine, Bd. II, 1907, p. 457-463.

gabbro, and its evident derivation from a gabbro magma also make it more like the hornblende peridotites.

Classified according to Johannsen's quantitative mineralogical classification,** it would occupy the following position:

**Johannsen, Albert, Suggestion for a quantitative mineralogical classification of igneous rocks. Jour. Geology, vol 25 63-97, 1917

Class	3
Order	3
Family	15
Number	3315

This hornblende peridotite is a differentiate of the gabbro of the sill, but the field data are insufficient to permit a satisfactory determination of the mode of differentiation. Because of its high specific gravity, and the fact that it is composed principally of a single mineral it might be suspected that gravity had something to do with its differentiation, but there is no evidence that such is the case. The hornblende peridotite lies at the top of a hill. It has a specific gravity of 3.32. It grades downwards, by decrease in hornblende and increase in plagioclase content, into a normal olivine gabbro with a specific gravity of only 3.18-3.19. The olivine gabbro becomes finer-grained at the base of the sill, and also heavier, as a result of an increase in magnetite content. The basal portion of the sill contains 12.9 per cent of magnetite, while a few feet higher it contains only 6.0 per cent. This may represent a differ-

entiation by gravity on a small scale, the magnetite having separated first and sunk to the base of the sill. The hornblende peridotite with its specific gravity of 3.32 can scarcely be considered a gravity differentiate of a magma whose maximum specific gravity may be estimated at about 3.25, when the heavy rock lies at the top of the mass. Of course it is not possible to determine, under the circumstances, whether the hornblende peridotite at the top of the mass as it is exposed at present really lies at the top of the sill or not. The actual top of the sill has been eroded. The mass dips to the southeast, but no exposures were found of its contact with the formation under which it dips.

GRANITE DIKES.

In the early reports of the Minnesota Geological and Natural History Survey, in the final report,* and in Clement's monograph** there are mentioned a number of dikes of red granite which cut the granite at several localities. Grant*** reports one locality at which the granite occurs in large masses which send offshoots into the surrounding gabbro. The dikes are said to vary in width from half an inch to ten feet and to consist of quartz, orthoclase, acid plagioclase, and biotite.

*Winchell, N.H., and others, The geology of Minnesota, Minnesota Geol. and Nat. Hist. Survey, Final Report, vol. 4, pp. 458 and 479, 1899.

**Clements, J.M., The Vermilion irom-bearing district, Minnesota Mono. 45, U.S. Geol. Survey, p. 422, 1903.

***Grant, U. S., The geology of Minnesota, Minnesota Geol. and Nat. Hist. Survey, vol. 4, p. 458, 1899.

This red granite bears a superficial resemblance to the much older Archean and Algonkian (Giant's Range granite, Snow-

bank Lake granite, etc.) granites, but it is intrusive in the Duluth gabbro, is of Keweenawan or post-Keweenawan age, and has seldom been found in large masses. It is here regarded as a hypabyssal phase of the red rock which is so abundant in the upper portion of the Duluth laccolith and which is frequently intrusive in it. It is more like Irving's "augite syenites"*

*Irving, R.D., The copper-bearing rocks of Lake Superior, Mono. 5, U.S. Geol. Survey, p. 112, 1883.

and Bayley's "granular red rock",** than any other of the red

**Bayley, W.S., The euptive and sedimentary rocks on Pigeon Point, Minnesota, and their contact phenomena, Bull. 109, U.S. Geol. Survey, pp. 50-53, 1893.

rocks which have been described.

On Gabimichigami Lake one of these dikes is found cutting both the gabbro and its fine-grained granulitic border phase. It is 11-12 inches wide and strikes N30 degrees W, and dips 80 degrees to 85 degrees SE. It apparently occupies a fault fracture, although there was no way to measure the displacement, which may have been slight. This possibility is of some interest in connection with certain metamorphic features shown by the gabbro.

That the dike occupies a definite fracture of some magnitude is indicated by the following features:

a. It was followed for a distance of about 600 feet along the strike with no deviations from a straight line that could be noticed.

b. For this distance one wall of the dike stands up as a low escarpment in almost continuous exposures. Masses of the granite are often seen "frozen" to the wall.

c. The coarse gabbro wall rock is often noticeably sheeted and sheared on either side of the dike for several inches, and

narrow stringers of the granite from a fraction of a millimeter to 2 inches wide, and ½ to 2 or 3 inches apart occupy these sheeting planes. Occasionally platy fragments of the gabbro are included in the dike.

Where both walls of the dike were seen in place, the dike outcrop occupied a depression several feet deep formed by the more rapid weathering of the sheared gabbro on either side, and the ready disintegration of the weathered granite itself.

Although the dike is very narrow, there is no sign of chilling along the contact. The rock is quite uniform in grain, the feldspar grains being about 0.2 to 0.5 cm. in diameter, and the quartz grains a little smaller. In addition to quartz, both pink and gray feldspar can be distinguished macroscopically, the latter sometimes showing twinning striations. A dull black mineral is present in small amount, and sometimes gives a gray tinge to the rock.

Chemical composition.-

The granite is closely related chemically to the Keweenawan "red rocks". A partial analysis was made for the writer by J. M. Lindgren and the results are indicated in column 7 of the table below, in which are given the available analyses of the red rock from various localities in Minnesota. The granite is most like the red rock whose composition is given in column 6. A noticeable feature is the relatively high soda content.

	1	2	3	4	5	6	7	8
SiO_2	66.36	65.56	71.15	73.28	71.81	61.09	61.89	72.42
TiO_2								0.40
Al_2O_3	13.33	10.06	12.40	11.83	12.82	15.34		13.04
Fe_2O_3	7.89	14.40	5.21	4.61	} 6.02	5.74		0.68
FeO	2.96	0.23	0.75	0.56		3.69		2.49
MnO								0.09
CaO	2.14	0.96	1.90	1.04	2.26	3.10		0.66
SrO								trace
BaO								0.15
MgO	1.20	0.73	1.13	0.36	0.56	1.33		0.58
K_2O	3.05	2.88	2.40	4.50	1.92	3.41	3.31	4.97
Na_2O	2.63	2.25	1.70	1.66	2.51	3.65	4.12	3.44
Li_2O								trace
H_2O	1.21	0.86	2.12	1.82		1.80		1.21
P_2O_5								0.20
Cl								trace
	100.77	97.93	98.76	99.66	97.90	99.15	....1.	100.37

Sp. Gr. 2.620

Analyses 1-6 inclusive were made by J. A. Dodge,*

*Quoted by Winchell, N. H., The geology of Minnesota, Minnesota Geol. and Nat. Hist. Survey, Final Report, vol. 5, pp. 89, 161, 188, 206, 400, and 303.

analysis 7 by J. M. Lindgren, and analysis 8 by W. F. Hillebrand.**

**Quoted by Bayley, W. S. The eruptive and sedimentary rocks on Pigion Point, Minnesota, and their contact phenomena, Bull. 109, U. S. Geol. Survey, p. 56, 1893.

Microscopic Characters.

In thin section the following minerals were recognized, and a careful measurement gave the proportions by volume indicated:

Orthoclase	36.3	
Quartz	29.7	
Albite	22.0	
Microcline	3.8	Johannsen's Family No.= 117.
Magnetite	3.3	
Biotite	2.2	
Zircon	0.2	
Kaolin & muscovite	2.0	Secondary.
Chlorite & calcite	0.5	Secondary.
	100.0	

The rock is a biotite granite. Although the section measured was cut from a chip selected at random from the main portion of the dike, inspection of hand specimens shows that it probably contains less than the average amount of biotite, since that mineral and magnetite are frequently present in sufficient amount to give a decided gray tinge to the rock.

In addition to the above minerals apatite is present in tiny prisms, but in such small amount that it does not appear in the geometric analysis. In one or two sections a few small grains

of pale green diopside were seen.

The order of crystallization is as follows:

1.Zircon, apatite and diopside.

2. Magnetite and biotite.

3. Quartz (idiomorphic).

4. Quartz and feldspar (albite and orthoclase).

Zircon and apatite occur in small prisms, often with excellent crystal form, the former being expecially abundant. Both of these minerals are nearly always found in the vicinity of magnetite grains. They are regarded as earlier because of their idiomorphism and because they occur as inclusions in biotite and magnetite.

The diopside is pale green, and occurs in small rounded grains. The magnetite occurs as aggregates or clumps of small grains, rather than in sharply defined single grains, and it may be a decomposition product of an older mineral. However, no trace was found in any of the sections examined (of which there were five) of any mineral other than those listed above. It is usually accompanied by shreds and flakes of biotite, with which it is intimately intergrown.

The biotite is a greenish-brown variety, varying in color from a brownish green to a deep brown. It does not occur in large plates, but in masses of small shreds which are bunched among and around clumps of small magnetite grains.

Most of the quartz grains are hypidiomorphic, with imperfect crystal faces, and rounded contours which suggest partial resorption by the magma. The curved outlines and irregular shapes of many of the grains give them the characters of the

"quartz de corrosion" of the French petrologists. They are frequently enclosed by feldspar, and then show well-developed prismatic and pyramidal faces. (Pl. XXII A) Holmquist* called

* Holmquist, P. J., Studien über die Granite von Schweden, Bull. Geol. Inst. Univ. of Upsala, vol. 7, pl 116, 1906.

this the "margination structure", and states "Alle diese Strukturzüge (quartz de corrosion, quartz vermicule) sind dem Granit und Gneiss der metamorphischen Gebiete eigen, und sie kommen in ganz unmetamorphosierten Graniten nicht vor". Bäckström** interpreted similar phenomena in Swedesh granite as follows: "The writer considers the differences from the hypid-

**Bäckström, H., Vestanåfaltet, K. Sv. Vet. Ak. Förh. vol. 29, No. 4, pp. 9-13, and p. 116, 1897.

iomorphic structure in these granites as owing to a sort of corrosion, but secondary not primary, due to the beginning of the crushing of the rock and probably also in some degree to the beginning of decomposition, and consequently not the result of circumstances accompanying the original crystallization of the granite magma." Eskola***, however, disagrees with most Fenno-

***Eskola, Pentti, On the petrology of the Orijärvi region in southwestern Finland, Bull. Comm. Geol. de Finlande, No. 40, p. 23, 1914.

Scandian geologists, who regard the "quartz de corrosion" as a secondary structure marking one of the most important differences between the Archean and post-Archean granites, and states, "In the opinion of the writer the simplest and most natural way to understand this structure is to regard it as a product of crystallization accompanied by magmatic corrosion. The physico-chemical theories of the crystallization of solutions have shown that the phenomena of resorption may take place as a normal event

in the regular course of crystallization, by reason of the progressive change of composition of the residual solution." The corrosion of the quartz in the granite of Gabimichigami Lake is best explained by magmatic corrosion, as postulated by Eskola.

Some of the quartz seems to have crystallized simultaneously with the feldspar, and the texture is granitic with quartz and feldspar grains mutually interfering and interlocking. The quartz contains abundant gas-and-liquid-filled cavities, and inclusions of glass. It often shows strain shadows and wavy extinction.

The orthoclase and albite crystallized simultaneously, and show mutually interfering and interlocking grains. The orthoclase is so turbid that its optical characters could not be accurately determined, but the high soda-content of the granite (see p. 78) indicates that the orthoclase is a sodic variety, perhaps anorthoclase. The albite is about $Ab_{90}An_{10}$. Both minerals are very much altered and turbid with a fine dust of kaolin, and contain many minute flakes of colorless to pale green sericite. Sometimes the sericite is so abundant that it forms a felted mass of flakes all through the feldspar. Other secondary minerals are chlorite and calcite.

The orthoclase nearly always shows irregular sinuous or wavy patches which are clear and almost unaltered. Between crossed nicols these patches show polysynthetic twinning, and occasionally show an indistinct grating structure. Where only one set of twinning lamellae are visible the symmetrical extinction is 18 degrees-19 degrees, while that of the albite grains is only 13 degrees-14 degrees. The material is, there-

fore, microcline. It is probably a pressure phenomenon, produced by the same forces which caused the development of strain shadows and wavy extinction. (Pl. XXII B)

Occurrence of myrmekite.

An interesting feature of this granite is the presence in it of the vermicular quartz-plagioclase intergrowth to which the name myrmekite was given by Sederholm.* This intergrowth con-

*Sederholm, J.J., Bull. Comm. Geol. de Finlande, No. 6, p. 108, 111-114, 1897.

sists of rods of vermicular quartz in plagioclase. Sometimes the plagioclase is striated and can be determined as an acid oligoclase. In other cases it is unstriated and can merely be determined as an acid plagioclase, since it has a higher index of refraction than adjacent orthoclase. The myrmekite frequently is present in the "wart-like" masses described by Sederholm, and these masses extend into orthoclase grains and present a convex surface toward them. (Pl. XXIII A and B). Many of the myrmekite grains in this granite look strikingly like those figured by Sederholm in a recent paper reviewing the whole field of such phenomena.** (Compare Pl. XXIII A and B) of this paper with figs.

**Sederholm, J.J., On syntantectic minerals. Bull. Comm. Geol. de Finlande, No. 48, 1916.

20, 21, & 22, Plate IV, and figs. 16, Plate III, and fig 37, Plate VII, of Sederholm's Paper)

After reviewing very completely the literature of the subject and comparing the views of different authors, Sederholm discusses the different characteristics of myrmekite point by point, as follows: (Page 134 et. seq.)

1. "Is the myrmekite always invasive into microcline or orthoclase? Most observers agree as to this point. The few cases in which myrmekite has been observed at the boundary of plagioclase and quartz may be explained by the fact that potash feldspar has earlier existed at the boundar, although it has been entirely replaced by myrmekite........... In general the myrmekite shows, as pointed out by Becke, convex outlines against the potash feldspar"

The myrmekite in the Gabimichigami granite aggrees well with all of these features. It is nearly always in contact with and invasive into orthoclase, and shows convex outlines against it. Some of the narrow stringers of granite consist almost entirely of quartz and myrmekite, and insuch cases there is no reason to believe that Sederholm's suggestion is not the true one; that is that the orthoclase has been completely replaced by myrmekite. In fact one can frequently find relicts of orthoclase which have not been completely replaced and can almost trace the gradation fromgrains of orthoclase which are just beginning to be replaced by a few grains of myrmekite, to those which have been completely replaced. A further significant feature is the presence of grains of quartz completely enclosed by myrmekite. Orthoclase often contains such inclusions and quartz was evidently left undisturbed when the mineral recrystallized to form myrmekite.

2. "Is there always a core of plagioclase? In a great many cases the myemekite is synantectic between primary crystals of plagioclase and potash feldspar,.......... Several authors

however have also observed cases which seem to deviate from this general rule. However, it is very difficult to prove that plagioclase cannot have existed as a core, at least in small quantities............. It is a striking fact that the formation of myrmekite never extends very far from the core, the diameters of the spindles or crusts never, in the cases known to me, exceeding 1 mm.

In the Gabimichigami granite there is practically always a core of plagioclase. Sometimes the plagioclase of the myrmekite is optically contimuous with a larger crystal of albite; more frequently the myrmekite lies between grains of plagioclase and orthoclase. In the small stringers of granite the myrmekite is especially abundant between the labradorite of the gabbro wall-rock and the orthoclase of the granite, invading the latter. None of the myrmekite masses had a diameter greater than 0.5 mm.

3. "From where has the material of the myrmekite been derived? The myrmekite like other synantectic minerals has not originated simply as a "reaction rim" by an exchange of material between the adjacent minerals. The plagioclase of the core has generally not been attacked, but has grown outwards by addition of material, and it was often, as just remarked, present in but very small quantities, at the moment when the crystallization of the myrmekite began. It is also impossible to think that its material was entirely derived from the potash feldspar which it has invaded. .... Material m ust have been carried in from without, and other material, especially potash, removed."

In the case of the Gabimichigami granite, it seems likely

that part of the lime and soda which replaced the potash of the orthoclase to form myrmekite may have been derived from the calcic feldspar of the gabbro forming the wall-rock of the dike. (Pl. XXIII A) The distribution of the myrmekite indicates something of that sort. A bare half dozen or so grains of myrmekite were found in the sections of the main dike, and these were all either adjacent to the wall-rock or to fragments of the wall-rock included in the dike. By far the greatest amount of myrmekite occurs in the small stringers of granite which run along sheeting planes parallel to the main dike, so that it is immediately adjacent to the feldspar of the gabbro, in which the requisite lime and soda are available. Sometimes parts of the stringers consist almost entirely of quartz and myrmekite. Other parts of the same stringer contain the usual orthoclase and albite in addition. Since these stringers are only a millimeter or a few millimeters in width, it would not require much transference of material in order to make the lime and soda available for the formation of myrmekite.

The labradorite of the wall rock is frequently turbid and altered to a mass of tiny colorless mica flakes. This alteration frequently takes place along cracks in the feldspar and extends inward on both sides of the cracks. This mode of alteration of the feldspar was found nowhere else in the gabbro except along the contact with the granite dike. Although no analysis is available and the mica flakes are too small for accurate determination, it is possible that the mica is a potash variety and that the potash set free when the orghoclase was re-

placed by myrmekite went into the mica of the altered labradorite. Thus we explain the derivation of the agents causing the change and the disposition of the products.

4. "Have the quartz and feldspar crystallized simultaneously? It is generally believed that the quartz and feldspar of the myrmekite have crystallized at the same time."

5. "Primary or secondary origin of the myrmekite. The authors who have discussed the petrogenetical question have arrived to widely different conclusions. In several cases they have changed their opinions in the measure as they have gathered more evidence.

"It has already been emphasized that myrmekite cannot be regarded as primary in the strictest sense of the work, since it has crystallized within the borders of another mineral, replacing its substance.

"Another question is whether the myrmekite is a product of the plutonic activity connected with the consolidation of the magma of the rock in which it occurs, or a formation of later date.

"I have here acoounted for a number of observations which seem to prove beyond doubt that the myrmekite of certain rapakivi granites, and also of older pre-Cambrian rocks, has been formed before the final consolidation of all the mineral constituents of the magma in question.........................

"But even if a great part of the myrmekite is a product of the plutonic activity which gave rise to the rock itself, it is not thereby proved that it should not in other instances be due

to a later metamorphism..............................

"The formation of the myrmekite may be either earlier, contemporaneous with, or later than the mechanical crushing of the rock, depending on the succession of the events at its metamorphism."

There seems to be a general agreement, according to Sederholm, that the process by which myrmekite is formed is a recrystallization of an isomorphous K-Na-Ca feldspar, or of orthoclase containing lime and soda in solid solution, by which plagioclase is formed. The potash is removed and the excess silica forms vermicular quartz rods in the plagioclase, the amount of quartz increasing as the plagioclase becomes more basic. Becke* and

*Becke, E., Über myrmekite., Mitt. der Wiener mineralog. Gesellsch., Tschermak's Min. u. Petr. Mitt. vol. 27, p. 381-390, 1908.

Luczizky** have measured many sections and shown that there is

**Quoted by Sederholm, loc. cit., p. 94.

such a relation between the amount of quartz and the basicity of the plagioclase. Such a process of recrystallization best explains the phenomena noted in the Gabimichigami granite, expecially since the orthoclase seems to be a sodic variety. (see p.78.)

It remains to be determined whether this process belongs to the waning period of the plutonic activity, connected with the eruption of the rock, or to the beginning of a later period of metamorphism. In one of the sections studied, showing the contact of the dike and wall rock, the minerals are fractured along a zone close to the contact, and slight displacement has taken place along the fractured zone. (Pl. XXIV A) This fracturing is probably due to slight movements after the solidifi-

cation of the granite. The significant feature in this respect is that myrmekite grains along the fractured zone are broken and the broken parts slightly displaced. This is regarded as good evidence that the myrmekite was formed prior to at least one period of metamorphism, and there is no evidence of more than one such period. With this in mind, it seems best to regard the myrmekitization in this case as a process connected with the last phases of the crystallization of the granite, rather than with a later metamorphism.

DIABASE DIKES

Cutting the Duluth gabbro and all older formations in the Vermilion district are great numbers of basic dikes, which have been described by Minnesota geologists and the geologists of the Us. Geological Survey. These dikes are abundant in the vicinity of Gabimichigami Lake. They show no particular differences from those over the whole district, as they have been described by previous workers in that region. Clement's* description gives a good idea of the general character of these rocks.

*Clement, J.M., The Vermilion iron-bearing district, Minnesota, Mono. 45, U.S. Geol. Survey, p. 422-424, 1903.

"Macroscopic characters---The rocks are invariably dark-colored, black or greenish or brownish black. The rocks in the smaller masses, the narrow dikes, show a very fine grain and could properly be called basalt. The rocks in the centers of the larger dikes show up as coarse-grained ophitic textured rocks and are dolerites. However, gradations between the fine and coarse-grained ophitic textured forms are shown in that the finer-grained basalts seem to predominate.

"<u>Microscopic characters</u>---Under the microscope, the rocks are found to be very fresh, as one would infer from the fact that they are usually decidedly black. In some few of them slight alterations producing greenish or brownish-green minerals tend to vary these to the brown or greenish tones already referred to. The constituents of the rock are yellowish to violet augite, green hornblende, a feldspar near labradorite in composition, olivine, apatite, ilmenite, and magnetite. These minerals show their normal characters, and but rarely give evidence of being altered. Where altered there has been produced chlorite, epidote, calcite, and hornblende. The ophitic texture predominates in these rocks, although the intersertal texture is also common and merges in places into an imperfect fluidal texture brought out by the parallel arrangement of the feldspars. Some of the rocks are porphyritic."

Grant* states that most of the dikes are not more than

*Grant, U.S., Geology of Minnesota, Minnesota Geol. and Nat. Hist. Survey, Final Rept. vol. 4, p. 459, and p. 479, 1899.

twenty feet wide, and again says "One of these dikes .... is peculiar in that it bears olivine, which has the same ophitic relation to the feldspars as does the augite."

The diabase dikes in the Gabimichigami Lake region vary in width from a few inched to about 30 feet. They are always chilled along their edges and are almost glassy in appearance, but microscopic study shows that they are always holocrystalline, although sometimes so fine-grained that the constituents cannot be distinguished.

One gets the impression from the above statement by Grant

that olivine is rarely seen in ophitic relation to the feldspar in these dikes. On the contrary every section studied from the coarser portions of the dikes on Gabimichigami Lake contains olivine which frequently lies in wedge-shaped and angular masses between the plagioclase laths. Even the fine-grained rock in a dike only eight inches wide showed this feature. The olivine is also found in rounded grains enclosed by the augite, and is, in fact, so abundant that the rock should be called olivine-diabase, rather than ordinary diabase, as it has been called. Measurement of one of these sections gave the following proportions:

Labradorite --------------55.2		Specific gravity ----- 3.00
Augite -------------------29.8		Johannsen's Family No.=2315
Olivine ------------------10.4		
Magnetite --------------- 4.6		
100.0		

Winchell* has given an analysis of what he calls the

* Winchell, A. N., Gabbroid rocks of Minnesota, Geologist, vol. 26, p. 274, 1900.

"normal diabase" and Bayley** gives an analysis of an olivine deabase from Pigeon Point, which give an idea of the chemical composition of the late Keweenawan deabases.

** Bayley, W. S., The eruptive and sedimentary rock on Pigeon Point, Minnesota, and their contact phenomena, Bull. 109, U. S. Geol. Survey, p. 37, 1893.

	1.	2.
SiO_2	47.90	49.88
TiO_2	0.57	1.19
Al_2O_3	19.92	18.55
Fe_2O_3	4.92	2.06
FeO	9.78	8.37
MnO	Trace	0.09
CaO	8.56	9.70
BaO	none	0.02
MgO	4.55	5.77
K_2O	0.56	0.68
Na_2O	2.75	2.59
H_2O	0.76	1.04
P_2O_5	----	0.16
Total	100.27	100.21
Sp. Gr.	2.89	2.923-2.970

1. Diabase, poor in olivine from the east side of Birch Lake on Nw $\frac{1}{4}$ Sec. 17, 61-11. Quoted by Winchell.

2. Olivine diabase from the extremity of Pigeon Point. Anslysis by Hillegrand, quoted by Bayley.

V. AREAL DISTRIBUTION OF FORMATIONS

ELY GREENSTONES.

The oldest rocks, the Ely greenstones, outcrop along the southwest shore and form the steep hill overlooking the lake. Their outcrops may be found all along the shore from a point south of the portage to Agamok Lake, in the S. E. $\frac{1}{4}$ sec. 36, T. 65 N., R. 6 W. to a short distance beyond The Narrows in the bay at the south end of the lake. (See map, Plate II)

OGISHKE CONGLOMERATE.

The Ogishke conglomerate is not exposed along the shore of the lake. Clements* has mapped a narrow strip of conglomerate along the northern border of the mass of greenstone, but no exposures of such a conglomerate could be found by the writer. Moreover, the slate to the north is quite fine-grained to within a few yards of the greenstone. Possibly the conglomerate is here represented merely by a slightly coarser phase of the slate formation which could not be found owing to scarcity of exposures along the contact. Typical Ogishke conglomerate, which is identical with that from the type locality on Ogishkemuncie Lake, occurs about one-fourth mile north of Gabimichigami Lake in secs. 29 and 30, T. 65 N., R 5 W., and extends north and east in a great mass.

KNIFE LAKE SLATES.

The Knife Lake slates occupy most of the area to the west, north and northeast of the lake. They outcrop along the west shore

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

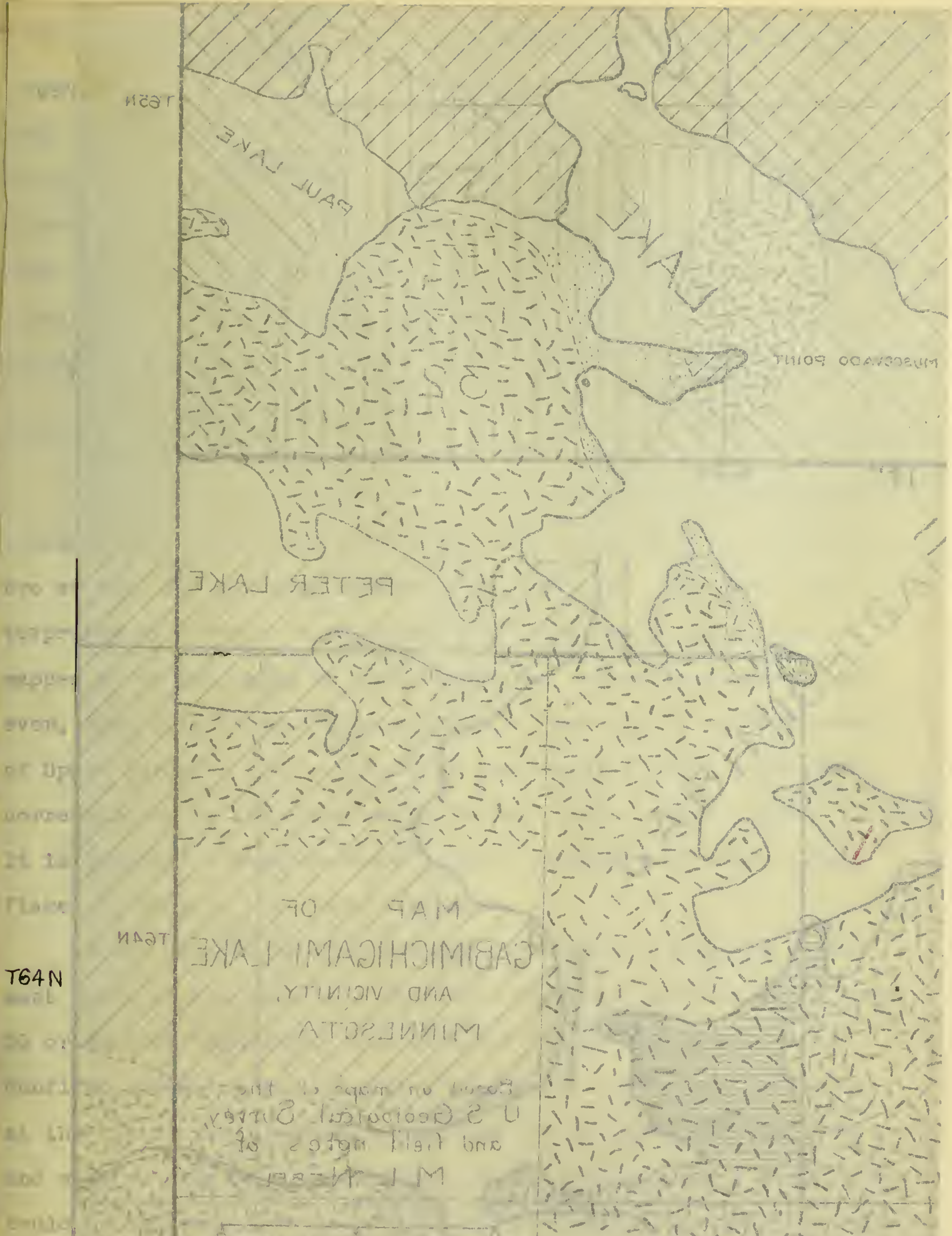
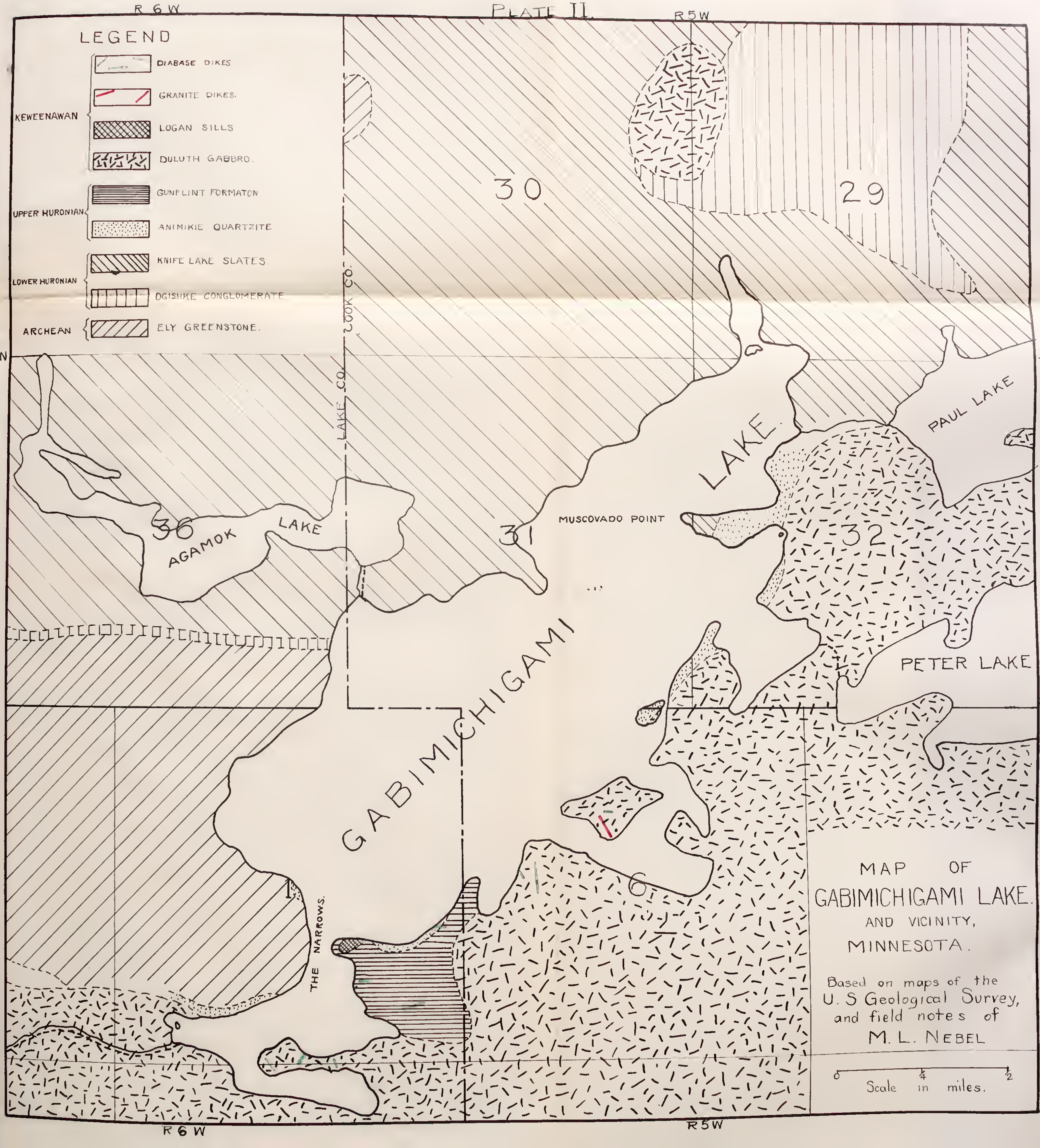

T64N

PLATE II.


R 6 W
R 5 W
LEGEND
DIABASE DIKES
GRANITE DIKES.
KEWEENAWAN
LOGAN SILLS
DULUTH GABBRO.
GUNFLINT FORMATON
UPPER HURONIAN
ANIMIKIE QUARTZITE
KNIFE LAKE SLATES.
LOWER HURONIAN
OGISHKE CONGLOMERATE
ARCHEAN
ELY GREENSTONE.
30
29
COOK CO.
LAKE CO.
T65N
PAUL LAKE
LAKE
MUSCOVADO POINT
36
AGAMOK
LAKE
31
32
GABIMICHIGAMI
PETER LAKE
THE NARROWS
6
T64N
MAP OF
GABIMICHIGAMI LAKE.
AND VICINITY,
MINNESOTA.
Based on maps of the
U. S Geological Survey,
and field notes of
M. L. NEBEL
Scale in miles.
R6W
R5W

from a point south of the portage to Agamok Lake to the north end of the lake, and on the east shore as far south as the long point extending out into the lake, and called by N. H. Winchell "Muscovado Point." The rocks on the west end of this point represent a portion of the Knife Lake slate formation which has been metamorphosed by the gabbro.

ANIMIKIE QUARTZITE.

At several points along the shore of the lake there are outcrops of a rock which has been very much metamorphosed by the gabbro so that its original character is obscured. This rock was interpreted by Clements as metamorphosed Knife Lake slate, and he mapped it as belonging to that formation. There is evidence, however, that this intensely metamorphosed rock is, in part at least, of Upper Huronian age, and that it represents a basal quartzite corresponding to the Pokegama quartzite of the Mesabi district. It is probably a metamorphosed arkosic quartzite in which large flakes of biotite have been developed.

About one-fourth mile east of The Narrows along the southeast shore of the lake this micaceous quartzite forms a bluff about 50 or 60 feet high which overlooks the lake. At this point the Gunflint formation was found conformably overlying the quartzite at the top of the bluff with the same dip as the underlying rock and with no sign of a depositional break between them. The bluff could be followed for several hundred feet along the shore and the two formations showed the same comformable relations with the same low dip to the southeast. The quartzite was about 40-50 feet thick with a few feet of iron formation above it. Here, then, the

quartzite evidently represents a basal formation of the Upper Huronian. No actual contacts could be found between these low-dipping formations and undoubted Knife Lake slates which would prove that the former are unconformable above the latter, but there is a decided discordance in dip between the two. As Clements states,*

*Clements, J. M., The Vermilion iron-bearing district, Minnesota, Mono. 45, U. S. Geol. Survey, p. 306, 1903.

however, there is nothing to prove that sufficient folding could not have taken place to account for the differences in dip. He sags "In the area referred to, the Lower Huronian rocks are extremely folded, and where this series is in contact with the Animikie, the vertical or steeply dipping rocks of the lower Huronian were found to strike in such a direction on the east side of Gobbemichigamma Lake as to bring them very nearly at right angles against the Animikie, which has a very low dip to the south, with a strike slightly north of east.........However, in view of the fact that some of the rocks were intensely plicated, it was recognized that it was possible for them to change both their strike and dip within a very short distance, even within the distance which separated them from the Animikie, and in which there was no exposures. Such a change might bring them into perfect conformity with the Animikie."

There is further evidence, however, that there is an unconformity below the quartzite. At one point on the west shore of the lake, just a little north and about one-fourth mile west of the quartzite outcrops on the east shore, was found an outcrop of the same rock. Here the exposures were few and it was not seen in contact with the greenstone, but greenstone occurs in the immediate

vicinity and is overlain by it. Here the quartzite seems to be directly above the Archean greenstone.

Again on the north shore of the bay south of the Narrows the quartzite outcrops for some distance, lying on the south slope of the greenstone mass. The quartzite lies along the border of the gabbro and between it and the greenstone. It has been mapped as metamorphosed greenstone by Clements, but examination of thin sections shows that it is petrographically identical with the quartzite at the first-mentioned locality. Chemical analyses of the quartzite from the two localities also show their similar nature. When compared with the accompanying analysis of the average greenstone from the Lake Superior region, the very different nature of the quartzite is evident.

	1	366	373
SiO_2	52.46	61.85	65.71
Al_2O_3	16.77	19.32	15.58
Fe_2O_3	3.92	as Fe_2O_3 9.06*	4.56*
FeO	5.44		
MgO	5.20	1.74	1.15
CaO	6.23	3.50	4.81
Na_2O	2.58		
K_2O	1.39		
H_2O	3.28		
TiO_2	0.45		
P_2O_5	0.16		
CO_2	2.14		
	100.00		

*Determined as Fe_2O_3

Analysis 1 is an average composition of the Lake Superior greenstones computed by Zapffe.*

*Zapffe, Carl, The effects of a basic igneous intrusion on a Lake Superior iron-bearing formation, Econ. Geol. vol. 7, p. 149, 1912.

Analysis 2 is of quartzite from the south bay of the lake.

Analysis 3 is of quartzite from the southeast shore of the lake.

Analysis 2 and 3 were made by J. M. Lindgren.

Still other evidence is furnished by the work of the early Minnesota geologists. When N. H. Winchell climbed the steep greenstone hill on the west side of the lake in 1887, he collected a series of ten specimens** as he ascended the hill. Later, sections were made of four of these specimens, and they were described by Professor Winchell.*** Of the four, three were evidently greenstones, representing metamorphosed basic volcanic rocks, but the fourth (No. 1367-C) is an entirely different rock. Professor Winchell states that "It contains a large amount of quartz, so much so as to make this the most evident and abundant ingredient......." He also mentions a dark, sub-opaque substance which surrounds quartz and feldspar grains. On examining this section**** it was found that the rock is a metamorphosed quartzite identical with the quartzite from the east side of the lake. The dark, "semi-opaque substance" is a mass of chlorite in which are imbedded myriads of tiny rutile needles and groups of needles, and it rep-

**N. H. Winchell, Minnesota Geol. and Nat. Hist. Survey, 16th. annual Rept., p. 93, 1888.

***loc. cit. Final Report, vol. 5, pp. 703-706, 1899.

****Kindly loaned by Dr. Emmons, Director of the present Minnesota Survey.

resents the decomposition products of large poikilitic biotite plates which enclosed quartz and feldspar grains. Occasionally, unchanged biotite can be recognized. Practically all sections of the quartzite from different places in the region show the same feature. Usually the biotite can be found in all stages of alteration in the same section.

Evidently here is a third point at which the quartzite lies directly on the Archean greenstones, and it seems probable that the quartzite once extended over this area and has not yet been completely removed by erosion. The metamorphosed character of the quartzite is also evidence of the previous extension of the gabbro laccolith over this area, about a mile north of its present northern boundary.

Farther north along the east side of the lake there are several points at which outcrops occur of a micaceous rock which is very similar petrographically to the micaceous quartzite at the south end of the lake. There is some local variation, however, and it is not possinle on a petrographic basis alone to assign these rocks definitely to the Upper or Lower Huronian. They have all been mapped by the U. S. Geological Survey as metamorphosed Knife Lake slate formation. They were not found in contact with either undoubted Knife Lake slates or Animikie rocks. However, there are certain structural relations which suggest that in part, at least, the micaceous quartzite is unconformable on Knife Lake slates.

At the west end of Muscovado Point, (Pl II) the rocks are nearly vertical, with a steep dip to the west. Further east along this point they have a low dip to the east toward the gabbro,

which outcrops at the east end of the point. N. H. Winchell noted this feature in 1886, and published a cross-section* showing these

*Winchell, N. H., Minnesota Geol. and Nat. Hist. Survey. 15th. Ann, Report, p. 380, 1887.

relations. No unconformable contact between the two could be found, however, and it is certainly possible, as Clements states, that there has been enough folding in this region to account for such a change in dip even within the short distance which separates them. There is, however, a decided petrographic difference between the two. A specimen taken from near the west end of the point is made up largely of greenish hornblende and plagioclase, and is very similar in composition to the graywackes just across the lake on the west shore, while a specimen from the east end of the point near the gabbro is made up of perhaps 50 per cent or more of quartz in rounded grains, with a large amount of orthoclase and albite. It also has numerous poikilitic plates of brown biotite, somewhat like those in the quartzite at the south end of the lake. It is evidently a sediment derived from the weathering of an acid rock, and was probably well sorted, as the grains are of nearly the same size. The other was just as evidently derived from the weathering of a basic rock (probably the greenstones) and is a poorly sorted sediment.

Clements emphasizes the non-siliceous nature of the contact-metamorphosed Lower Huronian sediments*, and says, "The mica- horn-

*Clements, J. M., The Vermilion iron-bearing district, Minnesota, Mono. 45, U. S. Geol. Survey, p. 344. 1903.

blende- and pyroxene-schists and gneisses derived from the slates by contact action of the gabbro almost invariably contain very little quartz, but are full of a rich-brown mica and hornblende,

with feldspar present in large quantity. The dark constituents predominate, and the mica is usually more abundant than the hornblende".

The rocks thus described contrast greatly with the micaceous quartzites on Gabimichigami Lake, and give further evidence of the great difference in character between the quartzites, and the normal lower Huronian sediments.

There is, then, good evidence that the micaceous quartzite which occurs along the east shore of Gabimichigami Lake at several points is a basal quartzite of the Upper Huronian, and not a part of the Knife Lake slates of the Lower Huronian. This evidence may be summarized as follows:

1. The quartzite lies conformably below the Gunflint formation of the Upper Huronian with the same dip and strike, and with no noticeable stratigraphic break.

2. It lies directly on the Archean at several points.

3. It has a low dip to the east and south, while the lower Huronian sediments nearby have a steep dip to the west.

4. It is much more quartzose than any phase of the Lower Huronian sediments which was observed in the region.

GUNFLINT IRON-BEARING FORMATION.

The Gunflint iron-bearing formation is the only Upper Huronian formation previously recognized in the vicinity of Gabimichigan Lake. It outcrops along the southeast shore of the lake and occupies most of the S. E. ¼ sec. 1, T. 64 N., R. 6 w. It is best exposed on the point of land which forms the east shore of The narrows, where it forms a steep bluff.

DULUTH GABBRO AND ASSOCIATED ROCKS.

The Duluth gabbro occupies most of the area to the east and south of the lake and its outcrops occur along the east and south shores of the lake from the base of Muscovado Point at the north end, to the west end of the little bay which forms the south part of the lake. Most of these outcrops are of a normal, coarse-grained olivine gabbro, but at several points there occur the different phases which have been described.

The very coarse-grained, pegmatitic phase outcrops along the bluff near the portage to Peter Lake, in the SW. ¼ sec. 32, T. 65 N., R. 5 W, and the whole face of the bluff is stained green with chrysocolla, derived from the weathering of chalcopyrite in the gabbro.

The fine-grained granulitic phase occurs on the southeast portion of the large island in the NW. ¼ sec. 6, T. 64 N., R. 5 W.

The norite phase of the gabbro occurs at the west end of the bay at the south end of the lake, both on a little island in the bay, and along the north shore.

The small outlier of ophitic gabbro lies about a half mile north of the lake in secs. 29 and 30, T. 65 N., R. 5 W.

The small mass which is probably one of the Logan sills occurs on the point which forms the east shore of The Narrows, and with it a black, hornblende peridotite.

Cutting the gabbro at the southeast corner of the large island referred to above is the granite dike, which runs N 30° W for several hundred feet.

At many places in the region diabase dikes cut the gabbro and

earlier formations. They are usually too small to be represented to scale on the map. The largest one observed was that which is about at the center of the south line of sec. 1, T. 64 N., R. 6 W. It is about 30 feet wide.

VI. STRUCTURE.

ARCHEAN GREENSTONES.

Gabimichigami Lake lies near the eastern end of a great synclinorium in the Archean greenstones, which is filled for the most part by Lower Huronian sediments. As the result of cross-folding, anticlines of greenstone, with Lower Huronian sediments on their flanks, are exposed at many places in the Vermilion district. Such is the structure of the Twin Peaks Archean anticline, as it is called by Clements,* which forms an east-west ridge of greenstone running west from the southwest corner of Gabimichigami Lake.

*Clements, J. M.; The Vermilion iron-bearing district, Minnesota. Mono, 45, U. S. Geol. Survey, p. 433, 1903.

LOWER HURONIAN SEDIMENTS.

On the north flank of this mass of greenstone lies a syncline of Knife Lake slates extending from a point south of Ogishkemuncie Lake, past the north end of Gabimichigami Lake and then east for nearly three miles. North of the slates is a great mass of Ogishke conglomerate, which lies on the south limb of another and a much greater anticline of greenstone, which runs almost due east and west for ten miles. Southeast of the Twin Peaks anticline, and lying between it and the gabbro, is a narrow monocline of Knife Lake slates extending from Kekekabic Lake nearly to Gabimichigami Lake.

The Knife Lake slates show the effects of pressure more than any other formation. They are very closely folded in many places, and have been very extensively jointed so that they break up into

rhomboidal blocks. Minor faulting has taken place along some of the joints, but the throw is seldom more than a few inches. Good cleavage has been developed in many places, and it is parallel to the bedding along the limbs of the folds, and nearly at right angles to it at the crests.* The slates show great variations in strike and dip over small distances, but the details of structure have never been worked out.

*Clements, op. cit. p. 302.

UPPER HURONIAN SEDIMENTS.

The Upper Huronian rocks in general have a low dip to the south in the Vermilion district.** Along the east shores of Gabimichigami Lake these rocks generally have a low dip to the southeast. At the western end of the area occupied by them, that is, near The Narrows at the south end of the lake, the Gunflint beds are considerably disturbed, and show some variations in dip. This is probably due to the intrusion of the gabbro sill at that point. Similar contortions in the Upper Huronian beds are known further east in the district where they are intruded by the Logan sills. The discordance in dip between the Knife Lake slates and the Upper Huronian quartzite near the north end of the lake has already been referred to. (p.98.)

**Clements, op. cit. p. 377.

DULUTH GABBRO

The Duluth gabbro is generally believed to be a laccolith.

This was first suggested by Grant in 1899*, and Clements** again

* Grant, Minnesota Geol. and Nat. Hist. Survey. Final Rept. v. 4, p. 326, 1899
**op. cit. pp. 416-417.

in 1903 came to the same conclusion. VanHise and Leith supported this conclusion in 1911.*** If it is a laccolith, it is, with one

***Van Hise and Leith, C. K., The Geology of the Lake Superior Region, Mono. 52, U. S. Geol. Survey, p. 202 and 373, 1911.

or two exceptions, the largest that has ever been described. It covers an area of about 2400 square miles****while the post-Cam-

****Elftman, A. H., The Keweenawan in Minnesota, Amer. Geologist, vol. 22, p. 132, 1898.

brian granite laccolith of Bushveldt,***** in the Transvaal, covers an area of about 10,000 square miles, and the anorthosite mass of the Saguenay district, Quebec, which Daly thinks is a laccolith, covers about 5800 sq. miles.*****

*****Daly, R. A., Igneous rocks and their origin, p. 53, 1914.

The Duluth gabbro has a dip of about 10 to the south for a distance of many miles, according to Van Hise and Leith.******

******op. cit., p. 373.

Its structural relations are very interesting. It is said to follow the contact between the Animikie and the base of the Keweenawan, in general, but in the Vermilion district it departs from that plane, and cuts across the Lower Huronian and even the Archean greenstones. It follows close to the base of the Animikie from near Gunflint Lake west almost to Gabimichigami Lake, and there it is supposed to cut across the Lower Huronian and the Archean.

It has been shown above, however, that much of the metamorphosed material on the east side of Gabimichigami Lake which has been assigned to the Lower Huronian is probably of Upper Huronian

age and belongs at the base of the Animikie. This rock was found resting directly on the Archean greenstones and between them and the gabbro, so that it seems probable that at least as far west as the west end of Gabimichigami Lake the gabbro was still following close to the base of the Animikie, and not cutting across the Lower Huronian and Archean. It is the old erosion surface at the base of the Animikie which cuts across these older rocks and the gabbro merely follows that surface. The fact that Animikie rocks (Gunflint formation) have been found along the north border of the gabbro several miles farther west, on Disappointment Lake, suggests that perhaps even that far west the gabbro was still following the base of the Animikie. This affords better proof than ever of the laccolithic nature of the gabbro.

Post-Keweenawan deformation.

It is probable that most of the folding and minor faulting of the Archean and Huronian rocks took place prior to the intrusion of the Duluth gabbro; indeed the greater part must have occured before Upper Huronian time, since the Animikie rocks are very slightly disturbed. They have a uniform, gentle dip to the south, except where they have been disturbed locally by the intrusion of the gabbro or the Logan sills. There is, however, some evidence that slight faulting has taken place since the intrusion of the Duluth gabbro. (See p. 76) This evidence may be summarized as follows:

1. Structural evidence. At one locality in the Gabimichigami Lake region a dike of granite cuts the gabbro and the footwall of the dike stands up as a low escarpment for a distance of

about 600 feet in a straight line. The coarse gabbro is often sheeted for a distance of several inches on each side of the dike, and stringers of granite lie along the sheeting planes parallel to the dike. This suggests that the granite was intruded along a sheared zone in the gabbro.

2. Microscopic evidence. In thin section the Duluth gabbro from the vicinity of the dike of granite, and from other points where there is no microscopic evidence of shearing, frequently shows metamorphic features which are best explained as due to dynamic metamorphism after the solidification of the gabbro. (See p.111) They are such features as might well accompany slight faulting.

VII. REGIONAL METAMORPHISM

ARCHEAN GREENSTONES.

The Archean greenstones are old basic effusive rocks which have suffered extensive metamorphism. This metamorphism has taken place under mass static conditions, and has consisted of a recrystallization of the rock constituents without destruction of the originaltextures to a very great extent. This process has resulted in the production of rocks consisting almost entirely of plagioclase and green hornblende, with crystalloblastic textures such as the blastoporphyritic, blasto-ophitic, etc. They are the plagioclase amphibolites of von Grubenman, produced under the conditions characteristic of his "meso-zone of metamorphism."

LOWER HURONIAN SEDIMENTS.

The Lower Huronian sediments of this region, the Ogishke conglomerate and the Knife Lake slates, also show the effects of regional metamorphism under mass static conditions, Dynamic effects are lacking. Pebbles of quartz have been partially or completely recrystallized to a mosaic of polygonal grains without destruction of the rounded pebble outlines. Feldspar pebbles have recrystallized to a less extent. The matrix has completely recrystallized to a mosaicof small quartz and feldspar grains in which lie ragged grains and fibrous masses of green hornblende. All other ferromagnesian minerals have disappeared except for small amounts of secondary minerals such as epidote, chlorite, etc. In the larger boulders of various rocks the same feature is noticed: the ferromagnesian minerals have recrystallized with the production

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of green hornblende in large amounts. The textures are the blasto-psammitic or blasto-psephitic of von Grubenman.

UPPER HURONIAN SEDIMENTS.

The Upper Huronian quartzite has been recognized only in the immediate vicinity of the Duluth gabbro, and it has been so thoroughly metamorphosed by the gabbro that it is not possible to ascertain to what extent it has been subjected to ragional metemorphism.

The Gunflint iron formation has likewise been so thoroughly metamorphosed by the gabbro in most cases that it is not possible to state just what effects are due to regional metamorphism. Grant*

*Grant, U. S., Contact metamorphism of a basic igneous rock, U. S. Bull. Geol. Soc. Amer., vol. 11, p. 508, 1900.

considered the original rock a glauconitic greensand with which there was more or less iron carbonate. This he believed was changed to quartz-magnetite-amphibole slates similar to the magnetite-actinolite slates or schists of other localities, the amphibole consisting of actinolite, cummingtonite, grünerite, or hornblende. These slates he believed were later metamorphosed by the gabbro to the rocks we now find. The changing of greensands containing ferrous silicates and ferruginous carbonates to magnetite-amphibole slates by regional metamorphism, was an anamorphic process requiring relatively deep-seated conditions such as those postulated by vonGrubenman for his"meso-zone." We know that such rocks have been produced in other parts of the Lake Superior district, but to prove that such extensive metamorphism had taken place prior to the intrusion of the Duluth gabbro is a difficult matter.

Clements* seems to ascribe the metamorphism of the iron-foundation entirely to the action of the gabbro without any intermediate metamorphism of an anamorphic nature. He described ferruginous cherts, containing granules of limonite, which he believed were produced by the oxidation of ferrous silicate rocks. He found structures in the metamorphosed rocks which indicated to him that they were produced by recrystallization of the ferruginous cherts. This would, however, involve a previous oxidation of the iron (a katamorphic process) to form the limonite granules.

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*Clements, The Vermilion iron-bearing district, Minnesota, Mono. 45, U. S. Geol. Survey, p. 384-387, 1903.

Zapffe** believed that the metamorphosed iron-formation rocks were developed directly from ferruginous silicate and carbonate rocks by contact metamorphism, without intermediate metamorphism of any sort. He states that it is unlikely that the contact rocks

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**Zapffe, Carl, The effects of a basic igneous intrusion on a Lake Superior iron-bearing formation, Econ. Geol. vol. 7, p. 167, 1912.

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were developed from ferruginous cherts, since such a change would involve a reduction of the iron, and this is an unusual change in the chemistry of the alterations of the Lake Superior iron-bearing formations.

Van Hise and Leith*** came to a similar conclusion.

***Van Hise, C. R. and Leith, C. H., Geology of the Lake Superior region, Mono. 52, U. S. Geol. Survey, p. 549-550, 1911.

It seems probable that contact-metamorphism by the Duluth gabbro alone produced the present characters of the iron-formation and that they are not in the least due to regional metamorphism.

DULUTH GABBRO.

The Duluth gabbro gives evidence of having been metamorphosed subsequent to its solidification. This evidence is as follows:

1. Broken and strained plagioclase. The plagioclase is broken and strained in nearly every section examined by the writer. Sometimes the fracturing has resulted in a slight granulation, and frequently the twinning lamellae are slightly displaced on opposite sides of fractures. Bent twinning lamellae and secondary lamellae developed by pressure are common phenomena.

2. Corona-like intergrowths or symplektites of plagioclase and pyroxene. In many sections an intergrowth of plagioclase and augite lies along the contact of labradorite with olivine, biotite, or magnetite. This intergrowth is described elsewhere (p), and it is shown that its origin is probably connected with metamorphic processes which operates after the main period of crystallization.

3. Alteration of augite and olivine. Although the augite and olivine of the gabbro are as a rule quite fresh, there are some localities at which they have been completely altered to secondary products, and the gabbro consists entirely of plagioclase and hornblende, or of plagioclase, hornblende, anthophyllite and biotite. In sections which show the greatest alterations of this sort the plagioclase shows greater metamorphic effects than usual. It is believed that the metamorphism varied in intensity from place to place, and that these greatly altered phases of the gabbro lie at the points where metamorphism was most intense.

The sheared gabbro alongside the granite dike described above (p.) contains augite in all stages of alteration. The alter-

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ation begins with the formation of a narrow rim of green hornblende around the borders of the grains. It does not form a smooth, continuous rim, but consists of sharp blades which penetrate the augite along cleavage cracks, and penetrate the surrounding plagioclase. A further stage in the process of alteration is the production of a rim of biotite around the hornblende rim. All transitions may be traced from a stage in which a few tiny blades of biotite penetrate the outer edge of the hornblende rim and extend well into the surrounding labradorite, to a stage in which the hornblende is completely surrounded by a broad band of biotite with its cleavage planes roughly perpendicular to the outline of the original augite grain. (Pl XXV A & B) When the alteration has gone this far there can be little doubt that reaction has taken place between the augite and the adjacent plagioclase. Sharp blades of biotite penetrate the plagioclase, and where idiomorphic crystals of the latter were partially enclosed by the augite their outlines have become rounded and they have been perhaps half replaced by the biotite. The rims, whether they are single, consisting of hornblende alone, or double, consisting of hornblende and biotite, must be considered true reaction rims.

In all cases the alteration of the augite is accompanied by the separation of tiny needles, which are probably ilmenite or rutile, since the augite is a titaniferous variety, and of thin plates which are believed to be rutile. In some of the sections studied the augites were cut so that the plane of the rutile plates lay parallel to the plane of the section. (Pl XXVI A) They are very thin translucent, violet plates with slight pleochroism from violet to a brownish violet.

The hornblende of the reaction rims is usually a bright-green kind, but it evidently varies in composition for a single grain sometimes varies in color. Sometimes the color is a pale green with delicate pleochroism in pale-green and bluish-green tints. Again it is a deep olive green, with strong absorption. Where the alteration of the augite is most complete, the central portion of the altered mass is usually a very pale-colored amphibole, sometimes with the properties of actinolite.

The biotite also shows great variation in color. In the reaction rims it may be pale-green, bright-green, brownish-green, or greenish-brown, grading to a deep chestnut brown in the vicinity of magnetite grains. The transition from green to brown may be very gradual, with all sorts of delicate intermediate tints. There is no sign of chloritic alteration.

Any olivine grains which may have been present have entirely disappeared. A few spongy masses of magnetite intergrown with biotite and anthophyllite are probably the alteration products.

The altered norite (p.   ) in which the hypersthene has been completely changed to a mass of actinolite and greenish or brownish anthophyllite, is another example of the extremes to which the alteration has gone in the metamorphosed gabbro.

4. Biotite rims around magnetite. The presence of rims of brown biotite around grains of magnetite is a feature shown by nearly every section of the Duluth gabbro. (Pl XV B and XVIII A) This phenomenon has been variously interpreted as being due to one or more of three processes: reaction between magnetite grains and residual magma surrounding them, reaction between magnetite and surrounding plagioclase due to the influence of mineralisers during

the last phases of the solidification of the rock, and reaction between the magnetite and surrounding plagioclase after the complete solidification of the rock and during a later period of metamorphism. Sederholm* has summarized the literature and the data bearing on this problem, and has shown that in some cases the biotite rim has been formed by the second process.

*Sederholm, J. J. On synantectic minerals, Bull. Comm. Geol. de Finlande, No. 48, pp. 2-5, 1916.

In the metamorphosed gabbro described above the magnetite is usually surrounded by biotite rims of unusual size, and the biotite of the rims varys in color. Close to the magnetite it is a deep brown, but if there is any hornblende or augite in the immediate vicinity the biotite grades into a green variety. The formation of the biotite was thus in part coincident with the formation of the hornblende, and the reaction between magnetite and plagioclase was probably going on during and due to the metamorphism of the gabbro. Of course there is nothing to show that this reaction did not begin during the crystallization of the rock, and that it was simply continued during the period of later metamorphism. This is a further illustration of the probability suggested by Sederholm*, namely, that there may be no sharp line between the last phases of plutonic activity connected with the final solidification of an intrusive rock, and the processes which produce what we call secondary minerals and structures, and which we usually ascribe to a later period of metamorphism.

*op. cit. p. 142.

There is a little evidence that some of the metamorphic features of the Duluth gabbro were produced during a period distinct-

ly later than the solidification of the rock. The granite dike which is intrusive in the gabbro has been subjected to shearing stresses since it solidified and granulated zones have been produced. (Pl XXIV A) In one instance where a grain of augite lay along the contact of the dike and the gabbro wall rock, a rim of hornblende has been produced, (~~and slender blades of green hornblende had been produced~~) and slender blades of green hornblende and green biotite penetrated the minerals of the granite dike, and extended entirely across a granulated zone in the granite. There was no sign of bending or breaking of the very slender blades such as must have taken place had they been present when the rock was granulated.

VIII. CONTACT METAMORPHISM

Effect of Duluth Gabbro.

ARCHEAN GREENSTONES.

The study of the contact metamorphism of the greenstones on Gabimichigami Lake was complicated by the fact that metamorphosed Upper Huronian quartizite occurs overlying the greenstones at the point where these rocks approach most closely to the gabbro. This metamorphosed quartizite was considered a contact phase of the greenstones in the field, and it was only after microscopic study that its true character was recognized.

The greenstones were not found in direct contact with the gabbro, but where they outcrop a few hundred feet away they show features which are probably the result of metamorphism by the gabbro. They are black or dark gray instead of green, and they have a granular appearance without the ophitic texture noticeable in the greenstones a half mile or more from the contact.

In thin section the difference is still more evident. The rocks still consist principally of hornblende and plagioclase, with a little magnetite, but the hornblende is a dark brownish green, or brown variety instead of pale green as in the unmetamorphosed rocks, and magnetite is less abundant. Sometimes plagioclase laths remain and the ophitic texture is recognizable, but more frequently the feldspar has recrystallized to a mosaic of small polygonal grains and the texture is crystalloblastic. In some cases pale green diopside is present instead of the hornblende, or both may be present in the same section, either as small grains forming, with andesine, a granoblastic texture, or in large

poikiloblasts enclosing andesine grains. The diopside is regarded as having formed in place of the hornblende when the rock recrystallized. A small amount of pale blue tourmaline occurs in slender radiating crystals. It is quite similar in character to tourmaline found in most other rocks of the region where they have been metamorphosed by the gabbro, and is regarded as evidence that at least a small amount of gaseous material was contributed by the gabbro to the rocks which it intruded.

The features noted here agree for the most part with the metamorphic effects described by Grant* in 1900, except that he found hypersthene, and did not find tourmaline. Clements** notes similar features, but observed also the presence of hypersthene and biotite, Zapffe*** found that the greenstones in the Gunflint lake district contained a large amount of cordierite where they had been metamorphosed by the gabbro. He also found abundant hypersthene, and smaller amounts of biotite, chlorite, anthophyllite etc. His average mineral composition of metamorphosed greenstones shows 50.65 per cent of cordierite and 33.60 per cent of hypersthene. No such rock was found on Gabimichigami Lake which could possibly be interpreted as a metamorphosed greenstone. A cordierite-hypersthene rock was found, however, which corresponds very closely to his description, but it is clearly a part of the Gunflint iron formation.

*Grant, U.S. Contact metamorphism of a basic igneous rock. Bull. Geol. Soc. Amer. vol. 11, p. 511, 1900.

**Clements, J.M., The vermilion iron-bearing district, Minnesota, Mono. 45, U.S. Geol. Survey, p. 161 and p. 418, 1903.

***Zapffe, Carl, Effects of a basic igneous intrusion on a Lake Superior iron-bearing formation, Econ. Geol. vol. 7, p. 147, 1912.

LOWER HURONIAN SEDIMENTS.

The metamorphism of the Lower Huronian sediments by the gabbro extends to a distance of a half-mile or more from the northern border of the main gabbro mass and consisted principally in a recrystallization of the rocks and the production of biotite and sometimes garnet together with the introduction of considerable amounts of blue tourmaline.

Where the small mass of gabbro north of Gabimichigami Lake intruded the sediments the metamorphism is slight. The rocks at the north end of the lake show no features which could be attributed to the metamorphic action of the gabbro. They are composed of feldspar, quartz, and green hornblende with minor amounts of secondary minerals, and have a well preserved clastic structure. These general characters do not change until within a few yards of the contact with the gabbro. Close to the gabbro the slate has recrystallized so that the clastic structure is destroyed. Abundant needles and ragged grains of pale green hornblende lie in a fine mosaic of polygonal quartz and feldspar grains. Small plates of brown biotite are common, and small crystals of blue tourmaline are not rare. The biotite and tourmaline are evidently metamorphic products, as sections of the rock a hundred yards from the contact contain neither of them.

Coarse-grained graywackes and conglomerates are not so completely recrystallized as the slates. Pebbles of quartz are sometimes recrystallized to a fine mosaic, but the clastic structure is preserved. Biotite and blue tourmaline are both present in every section. Small needles of pale green actinolite are common,

and many of the quartz grains are partially surrounded by fringes of these needles which penetrate the quartz.

The most far-reaching effect of the main gabbro mass has been the introduction of tourmaline. Nearly every section of the slates and graywackes from the west and northwest sides of the lake contains a few crystals of bright blue tourmaline. It was found as much as a mile from the nearest gabbro. Northeast of the lake it occurs abundantly in the slates half a mile from the gabbro. The tourmaline occurs in long slender crystals or groups of radiating crystals, or in allotriomorphic grains. In one section it formed slender veinlets running nearly across the section. Along the northeast shore of the lake, and nearer to the gabbro, the rocks contain flakes of brown biotite, which becomes more abundant in the neighborhood of the gabbro. Recrystallization has taken place and the clastic structure is lacking. The rocks consist of a fine mosaic of quartz and albite, in which lie myriads of tiny actinolite needles and biotite flakes. Some of the coarse-grained phases contain green hornblende and pale green diopside. Along the northeast shore near the portage to Paul Lake large poikiloblasts of garnet have been produced. (Pl. XVI-B) Sometimes the rock consists almost entirely of garnet, but that mineral usually is present in the form of irregular poikiloblasts enclosing rounded grains of quartz and feldspar, and flakes of mica or grains of tourmaline. The garnet is pale pink in thin section, and is probably a "common garnet" containing a mixture of the grossularite, almandite, and andradite molecules.

Neither garnet nor tourmaline have been mentioned by previous

writers who have described the contact metamorphic effects of the gabbro. Grant* mentions the recrystallization of the rocks and the production of biotite, hornblende, and pyroxene.

*Grant, U.S., the geology of Minnesota, Minnesota Geol. and Nat. Hist. Survey, Final Report, vol. 4, p. 477, 1899.

Clements** describes the production of large quantities of biotite

**Clements, J.M., The Vermilion iron-bearing district of Minnesota Mono. 45, U.S. Geol. Survey, p. 419, 1903.

and states "This production of biotite has been accompanied by a recrystallization of the minerals of the rock, whereby the sedimentary structures are mostly destroyed and mica-schists and gneisses are produced. Immediately along the edge of the contact with these schists in the metamorphosed sediments, occur large quantities of ferromagnesian minerals, such as augite, hyphersthene, and browm hornblende."

No mica schists or gneisses were seen by the writer in the vicinity of Gabimichigami Lake, but such rocks were seen southeast of Snowbank Lake along the contact of the gabbro and the Knife Lake slates.

The metamorphism of the slates in the Gabimichigami area differs, then, from that previously described in that both garnet and tourmaline have been developed, in addition to mica, pyroxene, and amphiboles. The mode of occurrence of the garnet suggests that it has been formed by the recrystallization of constituents already present in the rock, under the influence of the high temperatures existing in the vicinity of the gabbro at the time of its intrusion. The tourmaline appears to have a different origin. It occurs in slender crystals or in groups of divergent crystals,

in narrow veinlets of microscopic size, and, in larger veinlets, in crystals ranging from a small fraction of an inch to about an inch in length. There can be little doubt that the tourmaline is a pneumatolytic product contributed by the gabbro.

UPPER HURONIAN SEDIMENTS.

Animikie quartzite.-

The Animikie quartzite is very thoroughly metamorphosed wherever it has been found in the vicinity of Gabimichigami Lake. It lies close to the gabbro and its present characters are believed to be due principally to the metamorphic action of the gabbro. It is such a rock as might be produced by the recrystallization of an arkose or a feldspathic quartzite. The abundance of calcite in some phases of the metamorphic rock suggests that the arkose or quartzite may have had a calcareous cement. Recrystallization of impurities accounts for the presence of cordierite, biotite, and small amounts of actinolite, hornblende, diopside, and hypersthene, and the accessories zircon, titanite, magnetite, and apatite are those which are commonly found in quartzites. Blue tourmaline occurs in many sections of the quartzite, and, as in the case of the Lower Huronian sediments, it probably is a pneumatolytic product contributed directly by the gabbro.

Gunflint Iron-Bearing Formation.

A study of thin sections gives a qualitative idea of the composition of the iron-formation in its metamorphosed condition, and the kind of changes which must have taken place in order to produce such a rock from a ferruginous sediment. The

relative importance of the different metamorphic processes, especially the processes of recrystallization of materials preexisting in the rock, and of transfer of material from the intrusive gabbro to the intruded sediment, cannot be accurately determined until beds or bands are found which can be traced without doubt as to identification from the unmetamorphosed or slightly metamorphosed condition of the original sediment to the thoroughly metamorphosed condition of the contact rock. This is not possible for the rock at Gabimichigami Lake, for there it is everywhere thoroughly metamorphosed.

Clements* has described ferruginous cherts and iron-bearing carbonates from the Gunflint Lake region which he believes represent the original or slightly metamorphosed sediments from which the highly metamorphosed rocks in the vicinity of the gabbro were derived, but he does not record any quantitative study of the change. He states (p. 383) "As we follow these rocks westward we find that they change somewhat, passing into ferruginous cherts and cherts which have been more or less completely recrystallized into relatively coarse-grained rocks that might be spoken of almost as quartzites — although they are not, as should be clearly understood, metamorphosed clastic sandstones — actinolite, grünerite, and magnetite rocks, in which there is practically no carbonate, or but very little." Again (p. 386) "The original rocks from which the iron-bearing rocks, and eventually these rocks, were derived, judging from analogy with the correlated iron-bearing formation of the Mesabi district, are

* Clements, J. M., The Vermilion iron-bearing district, Minnesota, Mono. 45, U. S. Geol. Survey, pp. 379-384, 1903.

supposed to have consisted largely of chert with a hydrous ferrous silicate, that which occurs in the green granules, with which is associated more or less iron, calcium, and magnesium carbonate. From rocks of this composition it is easy to see that the coarse-grained rocks, consisting of quartz, magnetite, olivine, hornblende, augite, and hypersthene, might have been derived by simple recrystallization, without presuming any transfer of material from the gabbro."

Zapffe* studied the iron formation near Gunflint Lake,

*Zapffe, Carl, Effects of a basic igneous intrusion on a Lake Superior iron-bearing formation, Econ. Geol. vol. 7, pp. 145-178, 1912.

and also concluded that the metamorphism took place without any appreciable transfer of material from the gabbro to the iron-formation. He studied all available analyses, and showed that the iron silica ratio was about the same for the ferrous carbonate rock and the cordierite-magnetite rock which he states forms the bulk of the iron formation at that locality. He concludes that there was no concentration of the iron prior to metamorphism by the gabbro, and that the metamorphism took place directly from ferruginous carbonates and ferrous silicates to the complex silicate-magnetite rocks, and not from ferruginous cherts. In order to account for the high alumina content of the cordierite-magnetite rock, he postulates the presence of considerable amounts of argillaceous matter in the form of ferruginous slates in the original formation.

A prominent feature of the iron formation where studied by Zapffe is the presence of pyrrhotite, both in the iron formation and the sills intruding it. A twelve foot layer consist-

ing of seven feet of iron formation and five feet of gabbro in two sills averages 14 per cent of pyrrhotite, and one slide contained 35 per cent. He concludes "that the iron-bearing formation was originally rich in pyrite, and that due to regional metamorphism, heat supplied by the intrusives changed the pyrite present to pyrrhotite; sulphur funes rose, and in a small measure perhaps combined with some of the ferrous iron available higher up in the series and thus accounts for the presence of the small amount of the pyrrhotite in the contact phase of the intrusive mass above, though the heat of the mass itself no doubt also prevented to some extent the formation of pyrite." His evidence is as follows: (p. 164)

1. Regarding the presence of pyrite in the original formation, he states (p.163) "That the original formation was rich in sulphur can be surmised from the analyses of these ferrous carbonates (see page 162), which show that in each sample the sulphur was present in amounts of about o.12 per cent, and these samples were not selected to show a sulphur content." Examining the table on page 162 we find that the only sulphur reported is in the FeS, which is present to the amount of 0.13 per cent, equivalent to 0.04 per cent of sulphur. Moreover, the analysis of the metamorphosed iron-formation on p. 161 of his paper, shows o.59 per cent of sulphur, or about fifteen times as much as that in the ferrous carbonates.

Again (p.164) he states "The various facies of the unmetamorphosed gabbro described by Winchell contain only a minute amount of pyrite, and in the calculation of the chemical composition of the average mass the sulphur content was a negligible amount......

In the lake Superior region the iron formation rocks, such as the ferrous carbonates, are known to be pyritic, and in fact this mineral is so abundant in places that the rock is essentially a mass of pyrite with minor amounts of iron carbonate. It is easier to conceive the pyrite to be original in an iron formation of an aqueoigneous type, as the Lake Superior iron formations prevailingly are, than to be abundant in the gabbroid rocks only at a place, as in this case, where this igneous mass is intrusive into or lies upon an iron formation."

It has been shown elsewhere in this report (p.44) that the gabbro does frequently contain sulphides at points far from any known iron formation and that these sulphides are of magmatic origin. However, the scarcity of sulphides in an igneous rock is no argument against the presence of sulphur-bearing compounds in the magma from which it was derived, and the contribution of such compounds to surrounding rocks. The fact that a granite, surrounded by contact-metamorphic sulphide deposits, contains little or no sulphides itself does not prove that the sulphides were not derived from the granite magma.

Zapffe says further (p.165) "Undoubtedly the Archean greenstones below were metamorphosed at the same time as the Gunflint iron-bearing formation, but these fail to show any pyrite in the parts studied. Had sulphur been contributed by the gabbroid rocks, then these metamorphosed greenstones ought to show a sulphur content." On the west side of Gabimichigami Lake, however, the metamorphosed Archean greenstones do sometimes contain pyrrhotite, and associated with it is chalcopyrite.

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Pyrrhotite and chalcopyrite were found associated together in the gabbro by the writer at the following localities in Minnesota :

1. Duluth, Minnesota, at small quarry east of Lincoln Park.

2. Gabimichigami Lake, at several points along the east shore.

3. Shoofly Lake, east shore near north end. (Sec.12, T. 64 N.-R. 7 W.)

4. Round Lake, southeast of Snowbank Lake, on south shore, (7, T63 N.-R. 8 W.)

They were found in gabbro contact rocks at the following localities:

1. Gabimichigami Lake.

In metamorphosed Upper Huronian quartzite along east shore.

In Archean greenstones, west of lake in S.E.$\frac{1}{4}$-Sec.36, T65 N. R. 6 W.

2. Shoofly Lake, one-fourth mile north of north end, in metamorphosed Knife Lake slates (Lower Huronian.)

3. Snowbank Lake, west shore, in sec. 34, T.64 N., R. 9W. (Pyrrhotite only)

Zapffe says again (p.165), "No doubt sulphur fumes were very abundant at the time of the intrusion, but it seems more likely that these would largely escape as sulphur dioxide rather than combine with iron to form pyrrhotite, except perhaps in a small measure. Furthermore, when pyrite is subjected to heat, the chemical composition is altered and the mineral takes on the composition of pyrrhotite."*

*Moissan, H., Traite de Chemis Minerale, vol. IV, Metaux, p.565.

(p. 126)

The constant association of chalcopyrite with the pyrrhotite is pretty good evidence that the latter was derived from some other source than that of recrystallized pyrite of sedimentary origin, especially since the chalcopyrite is frequently as abundant or more abundant than the pyrrhotite. The further association of pentlandite with these two in the quartzite as well as in the gabbro, in the vicinity of Gabimichigami Lake makes any theory other than that postulating the derivation of the sulphides from the gabbro magma untenable. Furthermore, the wide distribution of pyrrhotite and chalcopyrite associated together in the gabbro and its contact rocks shows that the gabbro magma was competent to furnish enough sulphur for all of the sulphides that have ever been described from its vicinity. When one considers the immense size of the Duluth laccolith, as compared with that of the Sudbury mass which has produced such quantities of sulphides, one wonders rather that larger deposits have not been found.

The introduction of sulphides and of tourmaline has been the only contribution from the gabbro during its intrusion, as far as the present evidence shows. There is nothing to indicate that the presence of such peculiar minerals as olivine, hypersthene, fayalite, etc., and the unusual associations of olivine and quartz, etc., (see p. 34) are due to any process except that of recrystallization of a rock which already contained the elements necessary for their production. This recrystallization took place under mass static conditions at the high temperature existing in the vicinity of a large intrusive igneous rock.

Effect of granite dikes .

The granite dikes which cut the gabbro at several localities were probably intruded while the gabbro was still hot. (See p.77) They show no chilling effects along their borders, but are uniformly coarse-grained, and evidently had ample time for slow crystallization. Under such conditions it might be expected that reactions would take place between the minerals of the wall rock and the acid magma of the dike rock. Certain features indicate that something of the sort has taken place. The most noticeable feature occurs where labradorite grains in the gabbro are in contact with the minerals of the granite. The quartz, orthoclase, and albite of the granite lie sharply against the magnetite, augite, or hornblende, (to which the augite is altered) of the gabbro, but between them and the labradorite of the gabbro there is always a narrow rim of acid plagioclase. Between quartz and labradorite the rim is usually broad and shows fine albite twinning lamellae, with the extinction of acid oligoclase. Between albite or orthoclase and the labradorite it is usually very narrow, and cannot be determined accurately, except that it has a higher index of refraction than the albite of the granite. There seems to be a gradual change in composition from that of the labradorite to that of the rim of acid plagioclase, and there is no sharp line between them, Between crossed nicols there is an undulatory extinction between the two. It seems clear, particularly where the rim is broad, that it has originated by a partial recrystallization of the labradorite, and the absorption of some soda and silica from the granite magma. In most cases it

IX. ECONOMIC FEATURES

Gunflint iron-bearing formation.-

Some portions of the Gunflint formation consist very largely of magnetite, and attempts have been made to mine the deposits for their iron content. The principal effort of this sort was made at Paulson's Mine, about three miles west of Gunflint lake, but the project was found to be unprofitable and was abandoned many years ago. The following analyses of the magnetic iron ore are quoted by Clements*:

*Clements, J. M. The Vermilion iron-bearing district, Minnesota, Mono. 45. U.S. Geol. Survey, p. 385, 1903.

Analyses of iron ores of Gunflint beds.

	1.	2.	3.	4.	5.
Fe...............	58.40	54.01	63.98	55.60	62.05
Mn...............	4.92	5.02	none	4.34	-----
SiO_2.............	8.22	9.37	8.90	10.02	7.14
A1203............	0.52	0.07	-----	0.34	-----
P................	0.036	0.032	0.028	0.042	0.113
Ti...............	none	none	trace	none	-----

No magnetite masses of any size were observed in the Gunflint iron formation on Gabimichigami Lake, and none have ever been reported. It is quite unlikely that any commercial deposits of iron ore will ever be derived from this source.

COPPER AND NICKEL SULPHIDES.-

Nickel ores have been reported from the Duluth gabbro, but apparently the actual mode of occurrence has never been described. Winchell and Grant state* that "nickel ore is found

is clear that the rim is a replacement of part of the labradorite, rather than an addition along its border.

In the small stringers of granite which border the main dike, (p.77) the rim is usually absent, and myrmekite grains lie between the minerals of the dike and the wall rock.

Effect of diabase dikes.

The diabase dikes which cut the gabbro and many of the older rocks of the district have chilled borders and were evidently intruded into cold rocks. They had little or no metamorphic effect on the rocks which they intruded, even on the most acid rocks. A thin section of the contact between a diabase dike and the Animikie quartzite shows no metamorphic features of the quartzite that could be attributed to the agency of the diabase. The contact is very sharp, except for a few places where the magma apparently penetrated porous places in the quartzite and little areas of diabase lie isolated in the quartzite for a distance of a few millimeters from the contact.

Clements*, however, states that where the diabase dikes are in contact with the Rove slates (Upper Huronian slates in the eastern portion of the Vermilion district) "observation showed that the slates were indurated in the vicinity of the dikes, this induration diminishing as the distance from the dikes increased." The character and degree of the metamorphism were not determined.

In some cases, then, the diabase appears to have had some metamorphic effect on the rocks which it intrudes.

*Clements, J.M.., The Vermilion iron-bearing district, Minnesota, Mono. 45, U.S.Geol. Survey, p. 424, 1903.

[illegible]

Collins* has described diabase sills and dikes of Keweenawan age from the Onaping map-area Ontario, which metamorphosed

*Collins, W.H., Onaping map area, Memoir 95, No. 77, Geol. Series, Canada Geol. Survey, pp. 84-99, 1917.

Huronian sediments for 2 or 3 feet from the contact. The metamorphism consisted in recrystallization, albitization, and apparently the introduction of soda, where graywacke is the contact rock. Quartzites were rendered glassy by secondary enlargment of grains, and were partially fused.

*Winchell, N. H., and Grant, U. S., Geology of Minnesota, Minnesota Geol. and Nat. Hist. Survey, Final Report, vol. 4, p. 344, 1899.

in small amount in the gabbro, and many important finds of this ore have been reported, but as yet none of them have been substantiated." They elsewhere** give an analysis of a titaniferous magnetite in which 0.41 per cent of nickel was reported. Clements states*** that "a great deal of money has been spent in exploring for nickel ore, which has been reported as occurring in the titaniferous magnetites in the gabbro", and refers to the above analysis quoted from Winchell's report.

**op. cit., vol. 5, p. 496, 1900.

***op. cit., Mono. 45, p. 420, 1903.

The writer found small amounts of chalcopyrite and pyrrhotite in the gabbro at many points, (see p. 44) and on examining polished surfaces of these sulphides under the microscope found that the nickel-iron sulphide pentlandite, (Fe, Ni)S, is usually associated with them. The sulphides also occur in the contact-metamorphosed rocks along the northern border of the gabbro. Occasionally small masses consisting largely of sulphides occur in these rocks. The largest mass of this nature seen by the writer was found on the west side of the small island in Gabimichigami Lake which is crossed by the line between T.64 N. and T.65 N. The mass lies in a metamorphosed quartzite about 25 feet from its contact with the gabbro, which also contains the same sulphides in small grains. The mass is about a foot wide and was exposed as a narrow band for a distance of three or four feet. It consists of a crumbling, granular aggregate of rusty material in which may be seen many plates of a gray mineral with metallic luster. The

freshest material that could be obtained was badly weathered and veined with limonite. In addition to the gray metallic mineral just mentioned, smaller amounts of pyrrhotite, bright yellow chalcopyrite, magnetite and some dark silicates can be recognized macroscopically.

In thin section the silicates are seen to make up a very small part of the mass. (Pl. XXVIII) They consist of sugite, olivine, and plagioclase, with a few tiny flakes of colorless or brownish anthophyllite which are alteration products of the augite and olivine. The silicates lie in rounded, irregularly shaped masses surrounded by sulphides and magnetite. Olivine grains are nearly always surrounded by a rim of augite and some of the magnetite grains are small and rounded, and likewise are surrounded by rims of sugite. However, most of the magnetite, which is very abundant, lies in rounded masses which surround and embay the silicates. The sulphides also lie between and sometimes surround the rounded grains of silicates. The appearance in thin section is very much like that of the lean ore from Sudbury described and figured by Tolman and Rogers*.

*Tolman, C.F., and Rogers, A.F., A study of the magmatic sulfid ores, Leland Stanford Junior University publications, University series, p. 30 and Plate 2, Fig. 12. 1916.

Specimens of the rock and of the sulphide-bearing gabbro from the same place, were polished and studied under the microscope by the mineralographic methods described by Murdoch**. The

**Murdoch, Joseph, Microscopical determination of the opaque minerals, New York, 1916.

following opaque minerals were recognized: Pyrrhotite, chalcopyrite, magnetite, pentlandite, chalmersite (?), and an unknown grayish-white sulphide. The first four minerals were readily determined. The fifth occurs only in very small masses on which it is difficult to apply chemical reagents without overlapping adjacent minerals, but the color, hardness and chemical reactions as far as they could be determined correspond with those properties of chalmersite, as recorded by Murdoch. The properties of the sixth mineral do not correspond with any of the minerals described by Murdoch, and its identity could not be established. Its properties as determined on polished surfaces under the microscope are as follows:

Color.- White, with pyrrhotite grayish white, with chalcopyrite creamy white.

Hardness.- 3.5-4.5, about equal to pyrrhotite.

Surface.- Rough. The mineral has a very perfect cleavage in one direction, and is so brittle that it is very difficult to obtain a smooth polish. Its surface consists of alternate ridges and grooves parallel to the cleavage.

Microchemical tests.- (1)HNO_3 dil. Fumes tarnish brown; the mineral becomes brown and effervesces slowly with evolution of H_2S. Tarnish readily rubs off. (2)HNO_3conc. Tarnishes brown, effervesces rapidly with evolution of H_2S, etches and blackens. (3)KCN. Negative. (4)HCldil. Acid becomes bright yellowish-green but does not attack mineral or tarnish it. (5)HClconc. Same. (6)Aq.Reg. Effervesces slowly and tarnishes brown. Tarnish rubs off. (7)$FeCl_3$. Negative. (8)HClhot. Like HCldil. (9)NH_4OHconc.

Slowly tarnishes light brown, rubs off easily.

These properties correspond most nearly to those of polydymite, Ni_4S_5, but that mineral is not attacked by NH_4OH, while the unknown mineral is. Moreover, the unknown mineral cannot be a nickel or copper mineral, since the rock contains only 0.22 per cent of copper and 0. 12 per cent of nickel, and there is sufficient chalcopyrite and pentlandite present to account for all of that, while the unknown mineral is more abundant than either of those two.

In all of the sections studied there was a definite order of crystallization of the mineral. This order is as follows: (1)silicates, (2)magnetite, (3)chalmersite?,(4)pyrrhotite, (5)unknown sulphide, (6)chalcopyrite and pentlandite.

Much of the magnetite surrounds or cuts through the silicates and is probably younger. Relations such as those figured by Tolman and Rogers* are common.

*op. cit. Plate VII, fig. 34.

The chalmersite? occurs only in very small amount and was not found in direct contact with magnetite, but it is definitely older than pyrrhotite. It is regarded as younger than and has replaced pyrrhotite. The replacement begins around the borders of the pyrrhotite grains or along cracks. It penetrates the pyrrhotite in sharp blades or slender veinlets extending at right angles to the direction of the crack along which replacement starts. (Pl. XXIX-A and B). Replacement has gone so far that in most cases only a small core of pyrrhotite remains.

The chalcopyrite and pentlandite occur together in irregular masses which are younger than any of the other minerals, cutting

[illegible]

through them in narrow veinlets (Pl. XVII-A) or enclosing angular fragments which have not been replaced. The relation between the chalcopyrite and pentlandite is not so clear. The two are intimately associated, and although small masses of chalcopyrite occur without any accompanying pentlandite, the latter was found nowhere except in intimate association with chalcopyrite. The two minerals penetrate each other in long, sharp blades, or lie in narrow parallel bands with perfectly straight, sharp contacts. Probably the two were deposited at about the same time.

This small sulphide mass is evidently genetically connected with the gabbro. It contains the same silicates and the same sulphides which occur in the gabbro nearby, and the order of crystallization of these minerals is the same. (See p.42) It contains very little plagioclase, however, but has an abundance of minerals which are characteristic of the later phases of crystallization of the gabbro. It probably represents a small offshoot of the gabbro, intruded at a late period in the crystallization of the main mass.

This small deposit has many characteristics in common with the magmatic sulphide deposits. Tolman and Rogers* have studied these deposits and summarized their characteristics. The following features of the small sulphide deposit agree with these characteristics:

*Tolman, C. F., Jr., and Rogers, A. F., A study of the magmatic sulfid ores, Leland Stanford Junior Univ. Pub., Univ. series, 1916.

1. It is associated with a subsilicic igneous intrusive.

2. It contains most of the ore minerals classed as characteristic of magmatic deposits.

3. Pyrite is absent.

4. The ore minerals were formed at a late magmatic stage by a partial replacement of the silicates.

5. There is a definite order of formation of the ore minerals which is characteristic of magmatic deposits of this type.

X. SUMMARY AND CONCLUSIONS.

Section I of this paper contains a statement of the problem undertaken and acknowledgements of assistance.

Section II contains a brief history of previous geologic work done in the region studied, and of previous studies of the contact metamorphism of the Duluth gabbro.

Section III contains a brief description of the general features of the region, including stratigraphy, topography, relation of topography to structure, exposures, soil, forests, game, etc.

Section IV contains a detailed petrologic study of the rocks found in the region. The oldest rocks are Archean greenstones, which are described as plagioclase amphibolites. The [redacted] Huronian sediments include conglomerates, graywackes, quartzites, slates, and an iron formation, all of which have been partially or completely recrystallized since their deposition. The Keweenawan igneous rocks include the Duluth gabbro, the Logan sills and granite and diabase dikes cutting the gabbro. The occurrence of nickel, copper, and iron sulphides in the gabbro is described, as is also an interesting corona-like intergrowth of plagioclase and pyroxene. Local phases of the gabbro are described including a norite, a hyperite, and a fine-grained granulitic gabbro. A peculiar hornblende peridotite is described as a differentiate of the gabbro in a Logan sill. A granite dike is described and is shown to be related chemically to the Keweenawan "red rocks." The diabase dikes are also described.

Section V contains a description of the distribution of the

rocks in the region. It is shown that certain micaceous contact rocks which have been mapped as metamorphosed greenstones are identical petrographically with other contact rocks which have been described as metamorphosed slates and graywackes. Evidence is given that much of the micaceous contact rock represents a metamorphosed quartzite which is probably a basal quartizite of the Animikie.

Section VI contains a discussion of the structure of the rocks of the region. The Archean greenstones form an east-west anticline on the north side of which is a syncline of Lower Huronian sediments. Truncating both the Archean and the Lower Huronian are Upper Huronian sediments with a low dip to the south or southeast. Following close to the base of the Upper Huronian is the Duluth gabbro, which also has a low dip to the south. The laccolithic nature of the gabbro mass is discussed and further evidence is given that it is a laccolith.

Section VII contains a discussion of the regional metamorphism of the different rocks. The Archean greenstones have been changed from basic effusive rocks to plagioclase amphibolites. The Lower Huronian sediments have undergone recrystallization and enlargement of grains. It is not possible to determine whether regional metamorphism had anything to do with the development of the present characters of the Upper Huronian sediments, since they have been subjected to contact metamorphism by the gabbro. The gabbro shows slight metamorphic effects.

Section VIII contains a discussion of the contact metamorphic effects of the intrusive igneous rocks. The principal effect of the gabbro was the widespread introduction of tourmaline, and the

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introduction of a small amount of chalcopyrite and pyrrhotite into the intruded rocks, and their thorough recrystallization near the contact. As a result of the recrystallization such minerals as biotite, hornblende, garnet, and cordierite were developed in the slates and quartzites, and garnet, fayalite, olivine (chrysolite), quartz, cordierite, hypersthene, bronzite, augite, diopside, hornblende, grünerite, cummingtonite, actinolite, anthophyllite, etc. were developed in the iron-formation. The greenstones were recrystallized and brown hornblende and diopside were developed. The granite and diabase dikes had little or no metamorphic effect.

Section IX contains a discussion of the economic features of the region. It is concluded that the Gunflint iron-bearing formation at this locality contains no valuable iron-ore bodies. Small masses of sulphides which are occasionally found in the contact rocks near the gabbro are described. It is shown they contain copper, nickel, and iron sulphides which are probably of magmatic origin, and were derived from the gabbro. No deposits of sufficient size or richness for commercial development were found.

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APPENDIX

Short biography of Merle Louis Nebel.

Place of birth: Clinton, Illinois.

Date of birth: March 27, 1892.

Education:

Grammar and high school: Clinton, Illinois.

University: University of Illinois, September, 1909 to date.

Degrees: B.S. in mining engineering, 1913.

M.S. in mining engineering, 1915.

Honors: Final honors, 1913.

Tau Beta Pi.

Sigma Xi.

Publications:

Specific gravity studies of Illinois coal, Bulletin 89, Univ. of Illinois Engineering Experiment Station, 1916.

Professional experience:

Field season 1912: Field assistant, Illinois State Geol. Survey.

Field season 1914: Assistant geologist, Illinois State Geol. Survey.

Field seasons of 1915-1916: Geologist, Denman Bros., Oil Producers, Chautauqua County, Kansas.

Plate III.

A panorama of a portion of the Vermilion iron-bearing strict showing the typical glaciated topography, and the abundance lakes. It also shows the results of the forest fires which have astated many parts of the district.

Plate III.

Plate III

Plate IV.

Plate IV.

A, Photograph of a portion of the Vermilion district in which vegetation has been almost entirely destroyed, leaving good exposures of the rocks everywhere.

B, Photograph showing the result of a light forest fire which merely charred and killed the trees, leaving most of them standing. Many of the charred trunks have been blown down by wind-storms, leaving a tangled mass through which travel is very difficult.

Plate IV

A.

B.

Plate V.

Plate V.

A, A view of Kekekabic Lake, one of the larger lakes of the Vermilion district, showing the abundance of islands, a com on feature of most of the lakes in the region.

B, Photograph of one of the long, smooth cliffs of gabbro which are so common in the vicinity of Gabimichigami Lake.

Plate V

A

B

Plate VI.

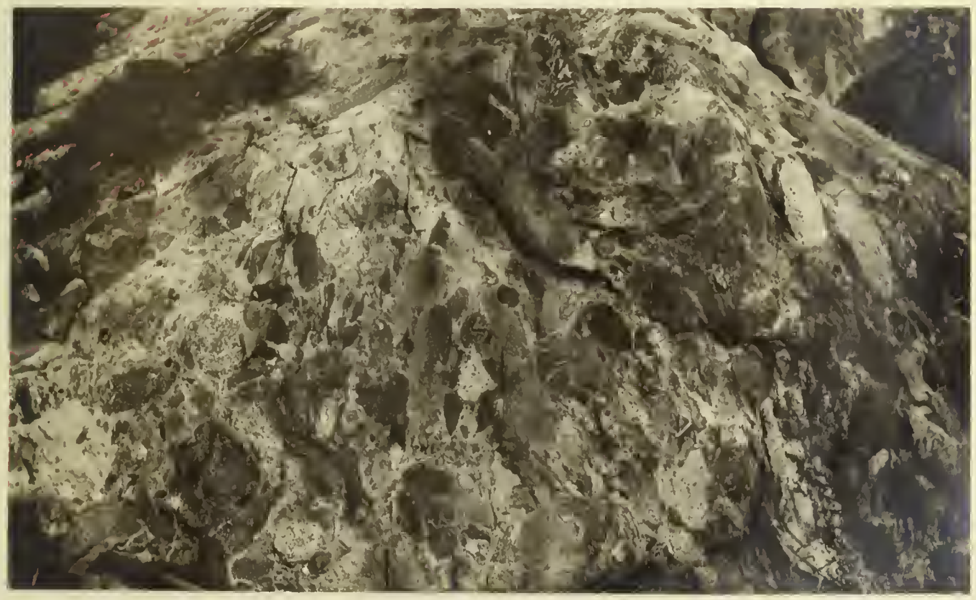
Plate VI.

A, Photograph of a cliff of Ely greenstone. Such cliffs are common topographic features in those parts of the region which are underlain by greenstone.

B, Photograph of an outcrop of Ogishke conglomerate, showing the heterogenous nature of the deposit. Several different kinds of light- and dark-colored boulders can be distinguished.

Plate VI

A



B.

Plate VII.

Plate VII.

A, Photomicrograph of a thin section of recrystallized Animikie quartzite, showing two large quartz grains with serrate borders, in a fine-grained matrix of quartz, feldspar, and calcite. Nicols crossed. x25.

B, Photomicrograph of a thin section of recrystallized Animikie quartzite showing large quartz grains enclosing rounded prisms of plagioclase and cordierite. The large white and dark gray grains are quartz, the two small prisms near the center are cordierite which is slightly altered to mica around the borders and the prisms in the upper left hand corner are twinned plagioclase.

Nicols crossed. x 44.

Plate VII

A

B

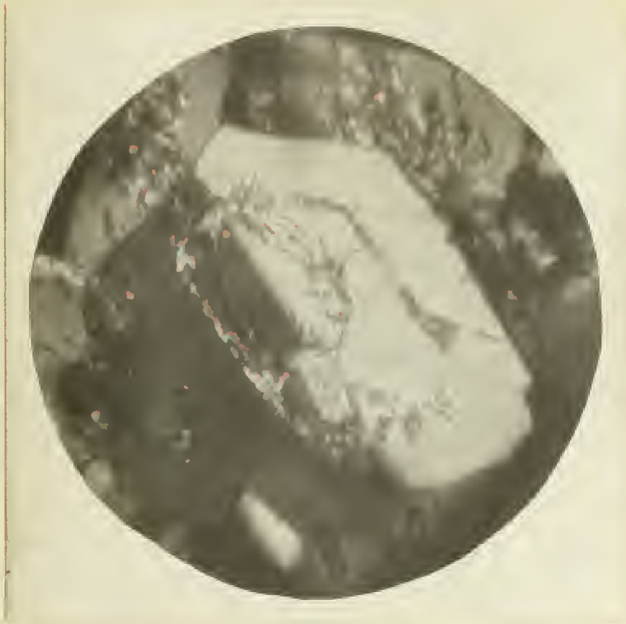
Plate VIII.

Plate VIII.

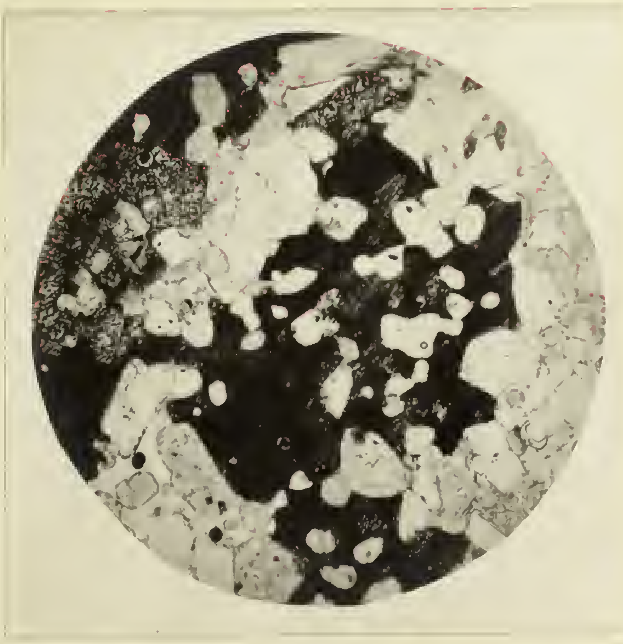
A, Photomicrograph of recrystallized quartzite showing enlargement of a feldspar grain. The outlines of the original rounded grain are marked by the alteration products.
Nicols crossed. x 205.

B, Photomicrograph of recrystallized quartzite showing the shape of the poikilitic biotite plates which are abundant in the rock. The black material is chlorite crowded with rutile needles, and is an alteration product of biotite. The white grains are quartz and plagioclase, and the light gray are cordierite prisms altered to mica.
Parallel light. x 47.

Plate VIII



A



B

Plate IX.

Plate IX.

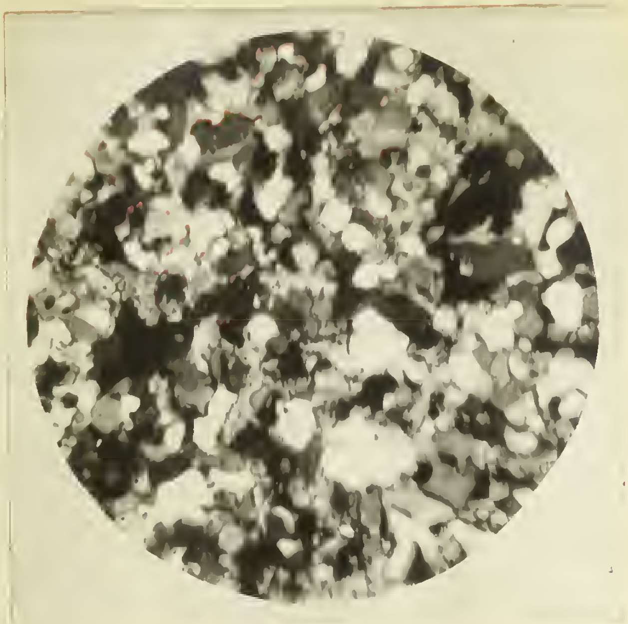
A, Photomicrograph of recrystallized quartzite showing calcite grains (light gray, with a rough or blurred appearance) in a mosaic with quartz and feldspar.

Nicols crossed. x 80.

B, Photomicrograph of portion of Gunflint iron-bearing formation rock consisting of grünerite(gray or black) which lies in fibrous masses between the quartz grains(white), and needles of which penetrate the quartz.

Parallel light. x 46.

Plate IX



A.

B.

Plate X.

Plate X.

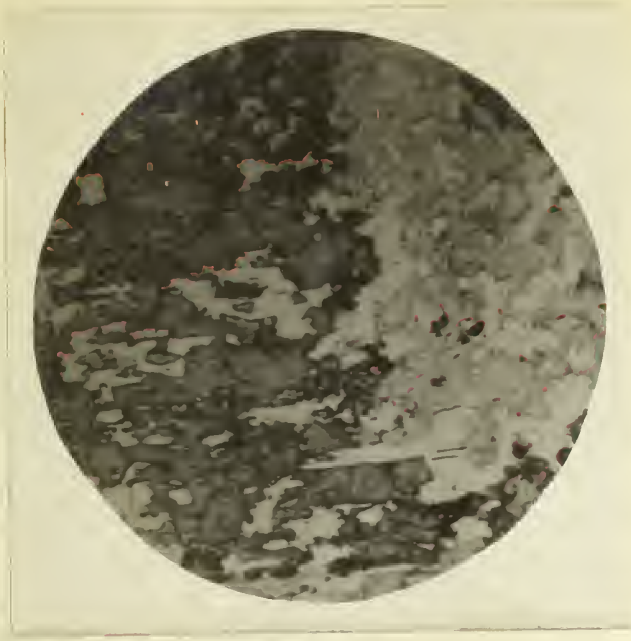
A, Photomicrograph of portion of the Gunflint iron-bearing formation, consisting of garnet(dark gray or black), calcite, (light gray and standing in relief) and quartz,(light gray with smooth surface).

Parallel light. x 36.

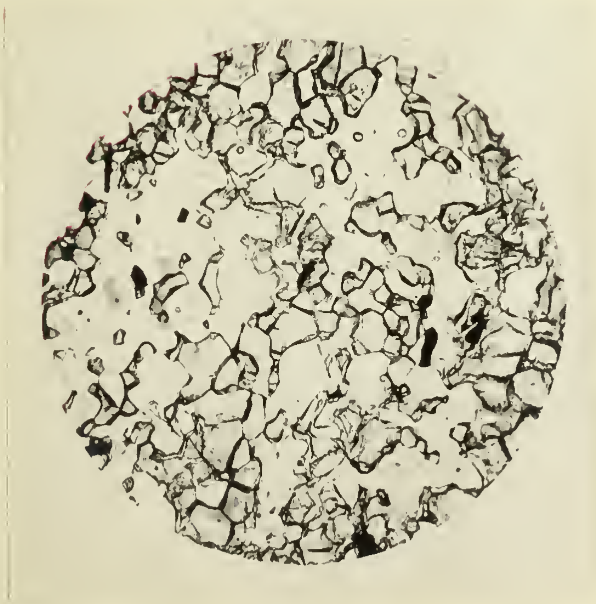
B, Photomicrograph of portion of Gunflint formation consisting of olivine(standing in relief) and quartz(white). A few grains of magnetite(black) are present.

Parallel light. x 44.

Plate X



A



B

Plate XI.

Plate XI.

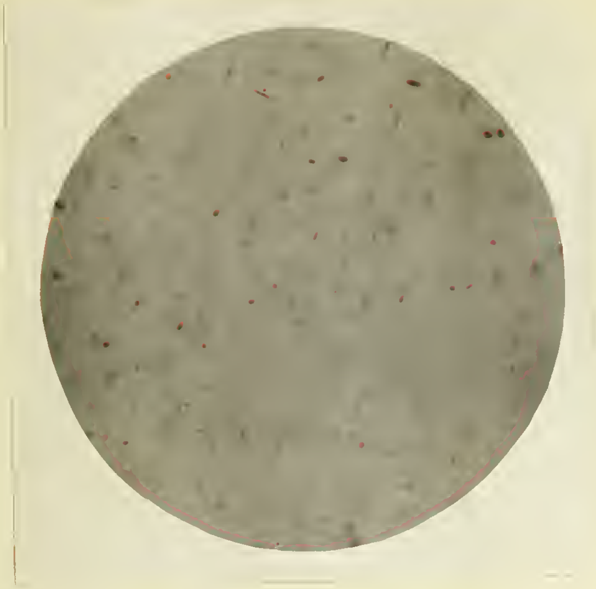
A, Photomicrograph of gabbro, showing tiny inclusions in the plagioclase.

Parallel light. x 710.

B, Photomicrograph of gabbro showing network of ilmenite needles in augite. The black crystal is magnetite.

Parallel light. x 76.

Plate XI



A

B

[illegible]

Plate XII.

Plate XII.

A, Photomicrograph of gabbro, showing relations between olivine (gray) and plagioclase(white). The olivine is younger and encloses laths of the plagioclase.

Parallel light. x 11.

B, Same with nicols crossed.

Plate XII

A.

B.

Plate XIII.

Plate XIII.

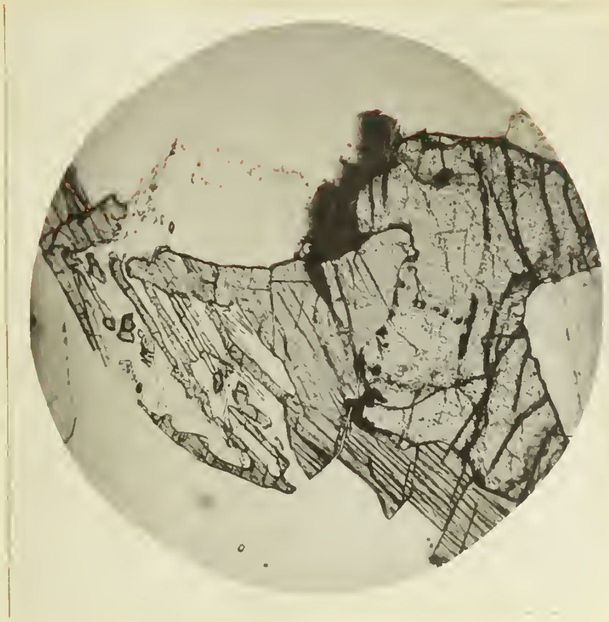
A, Photomicrograph of gabbro, showing a primary intergrowth of augite(gray mineral showing cleavage) and plagioclase(white). The gray mineral on the right, with irregular cracks crossing it, is olivine.

Parallel light. x 47.

B, Photomicrograph of gabbro showing an intergrowth of olivine and plagioclase. The olivine(gray) is partially altered to serpentine(black). The small grains of olivine are in optical continuity with the large grain.

Parallel light. x 58.

Plate XIII



A.

B.

Plate XIV.

Plate XIV.

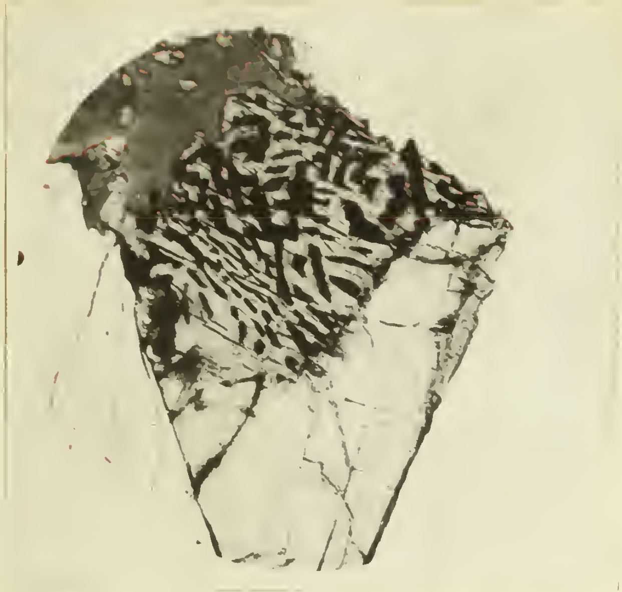
A, Photomicrograph of gabbro, showing an intergrowth of magnetite (black) and augite(gray). The light gray mineral below is olivine.

Parallel light. x 80.

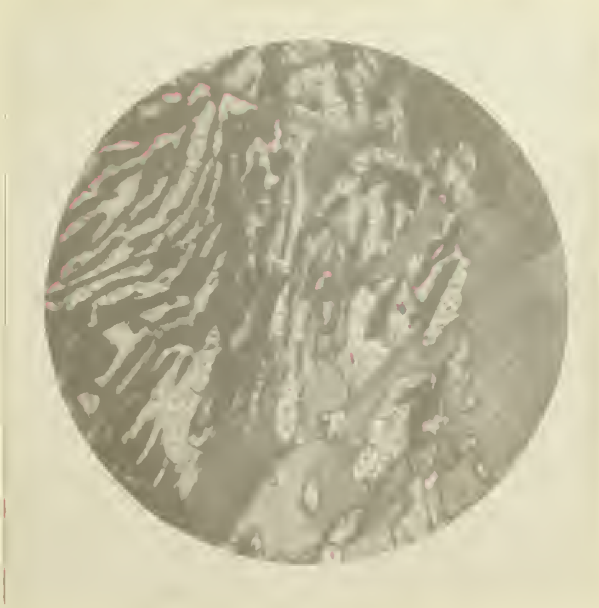
B, Photomicrograph of gabbro, showing a vermicular intergrowth of magnetite(black) and augite(gray with rough surface). On the right the magnetite has altered to biotite, probably by reaction with adjacent plagioclase, which is outside the field of view.

Parallel light. x 200.

Plate XIV



A.



B.

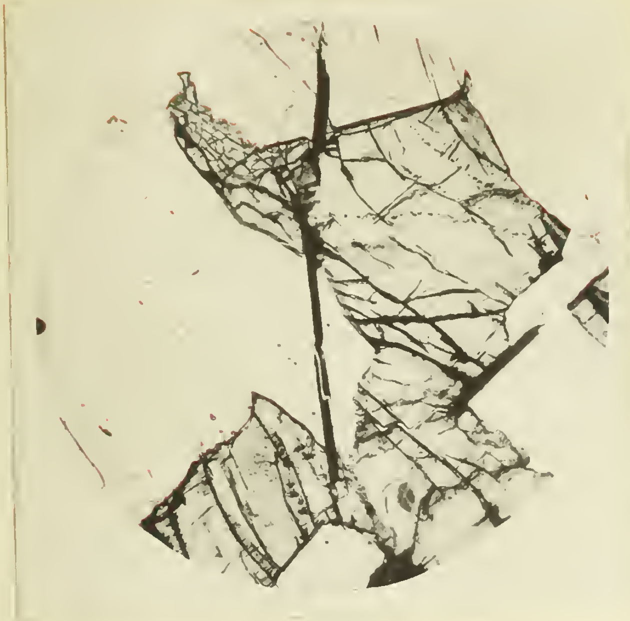
Plate XV.

Plate XV.

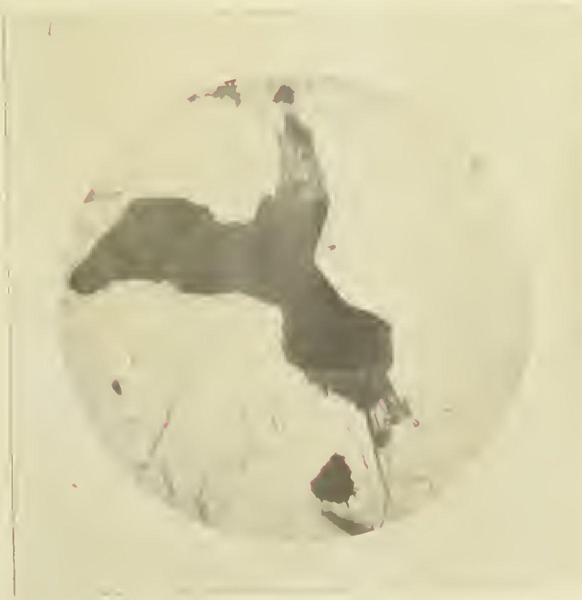
A, Photomicrograph of gabbro, showing a thin blade of biotite (black) penetrating olivine(gray, in relief), and cutting entirely through plagioclase(white). The fracture in the biotite was due to the breaking of the thin section. Parallel light. x 45.

B, Photomicrograph of gabbro, showing biotite(dark gray) on the contact between magnetite(black) and plagioclase(white), and sending slender, finger-like projections into the plagioclase. Parallel light. x 34.

Plate XV



A



B

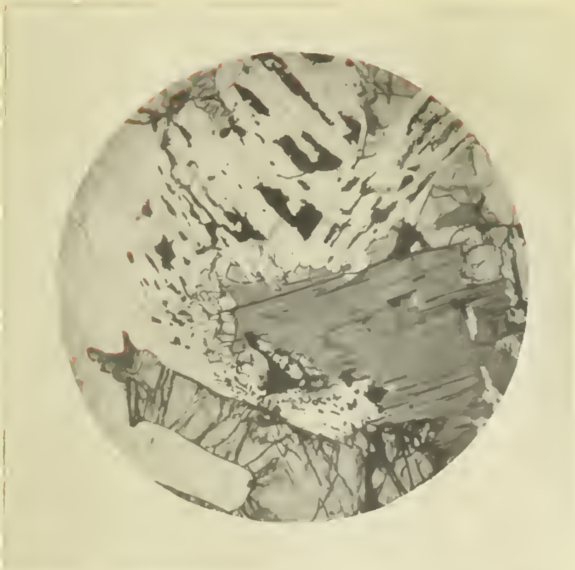
Plate XVI.

Plate XVI.

A, Photomicrograph of gabbro, showing grains of chalcopyrite and pyrrhotite(black) replacing plagioclase(white) parallel to the cleavage, and penetrating biotite(dark gray) along cleavage planes. The gray mineral at the bottom is olivine. Parallel light. x 20.

B, Same, with crossed nicols.

Plate XVI



A

B

Plate XVII.

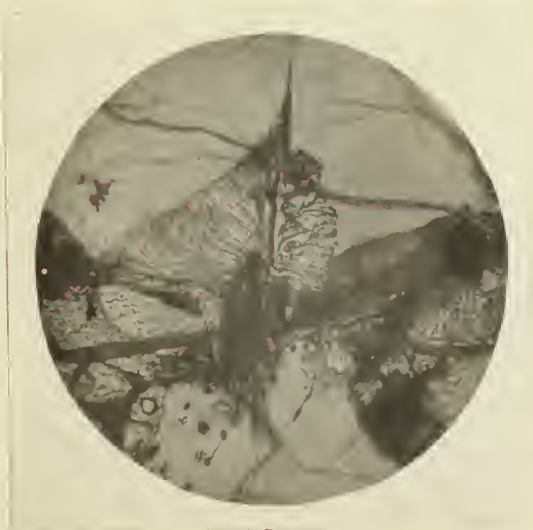
Plate XVII.

A, Photomicrograph of polished specimen of sulphides in gabbro, showing veinlets of chalcopyrite(dark gray) cutting through pyrrhotite(light gray). The black spots are pitts in the surface of the specimen.
Vertical illumination. x 590.

B, Photomicrograph of thin section of gabbro, showing a corona-like intergrowth of plagioclase and pyroxene surrounding a slender blade of biotite(standing in a nearly vertical position in the center of the photograph). The vermicular rods of pyroxene radiate from the biotite. At the top and bottom is plagioclase(light gray), and to the left and right are grains of olivine(gray, with a rough surface).
Parallel light. x 121.

Plate XVII

A



B

Plate XVIII.

Plate XVIII.

A, Photomicrograph of thin section of gabbro, showing the corona-like intergrowth surrounding a mass of biotite, which in turn partially surrounds magnetite. The magnetite seems to be later than, and invasive in the augite(dark gray, and full of cracks). At the bottom of the photograph is twinned labradorite.
Nicols crossed. x 20.

B, Photomicrograph of thin section of gabbro, showing plagioclase laths(white) enclosed by olivine(dark gray and full of cracks). The plagioclase has been almost completely replaced by the fibrous intergrowth of plagioclase and pyroxene, so that mere cores are left.
Parallel light. x 20.

Plate XVIII

A

B

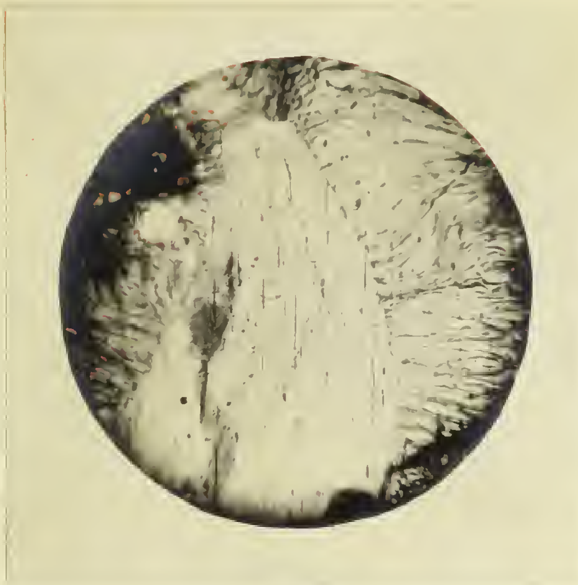
Plate XIX.

Plate XIX.

A, Photomicrograph of thin section of gabbro showing inclusions (black) in plagioclase(white) extending into the intergrowth which has replaced the plagioclase.
Parallel light. x 120.

B, Photomicrograph of thin section of hornblende gabbro from a Logan sill, showing a dense network of ilmenite needles(black) in augite(dark gray).
Parallel light. x 209.

Plate XIX



A

B

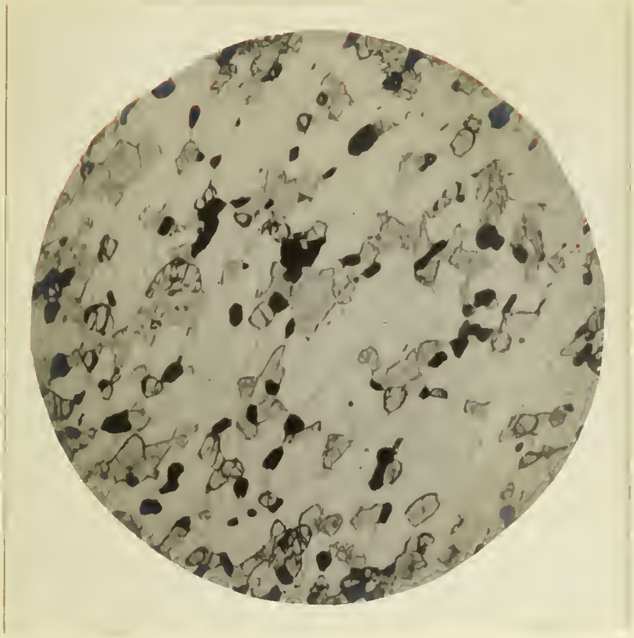
Plate XX.

Plate XX.

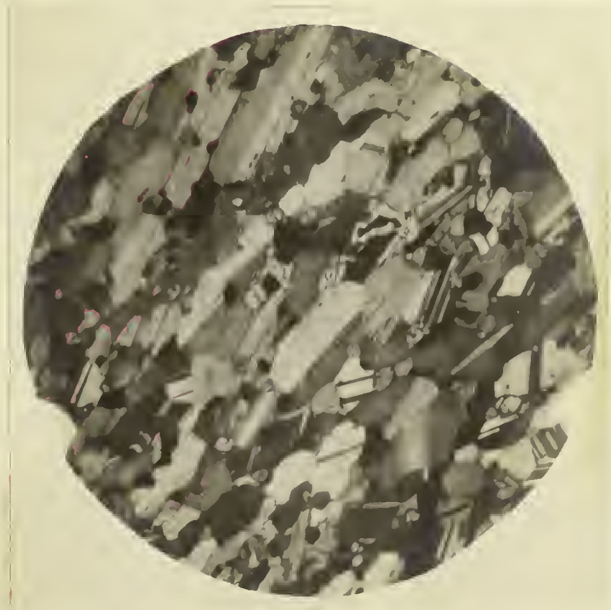
A, Photomicrograph of thin section of granulitic gabbro which has probably been recrystallized under pressure, resulting in elongation of the minerals and their parallel arrangement. Plagioclase is white, augite and hypersthene are light gray without much relief, olivine is darker gray, and stands in relief, and magnetite is black.

B. Same, with nicols crossed.

Plate XX



A



B.

Plate XXI.

Plate XXI.

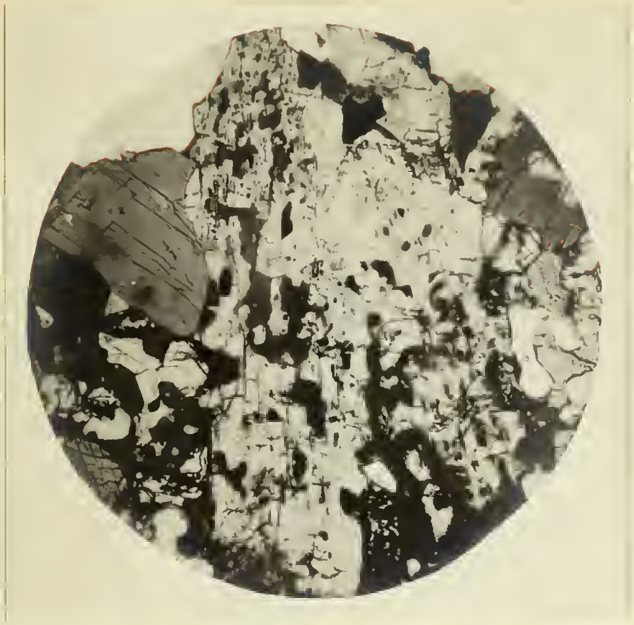
A, Photomicrograph of thin section of hornblende gabbro from a Logan sill, showing a large augite crystal(light gray) intergrown with brown hornblende(dark gray or black). The small areas of hornblende scattered through the augite are optically continuous with the large areas to the right and left at the bottom of the photograph. The small white areas on the right are plagioclase.

Parallel light. x 48.

B, Photomicrograph of a thin section of hornblende peridotite. The large light-gray area on the right is olivine enclosing a few grains of hornblende. The small light-gray areas are olivine or augite. The white areas are plagioclase(except for two or three holes in the section), and the dark-gray and black areas are brown hornblende. Several of the hornblende grains in the photograph show good basal cleavage.

Parallel light. x 16.

Plate XXI



A.

B

Plate XXII.

Plate XXII.

A, Photomicrograph of thin section of granite from a small dike, showing an idiomorphic quartz crystal with slightly corroded outlines. It ie enclosed by orthoclase(dark gray). Nicols crossed. x 162.

B, Photomicrograph of thin section of granite showing orthoclase, (dark-gray and turbid) with irregular areas of microcline. Nicols crossed. x 55.

Plate XXII

A

B.

[illegible]

Plate XXIII.

Plate XXIII.

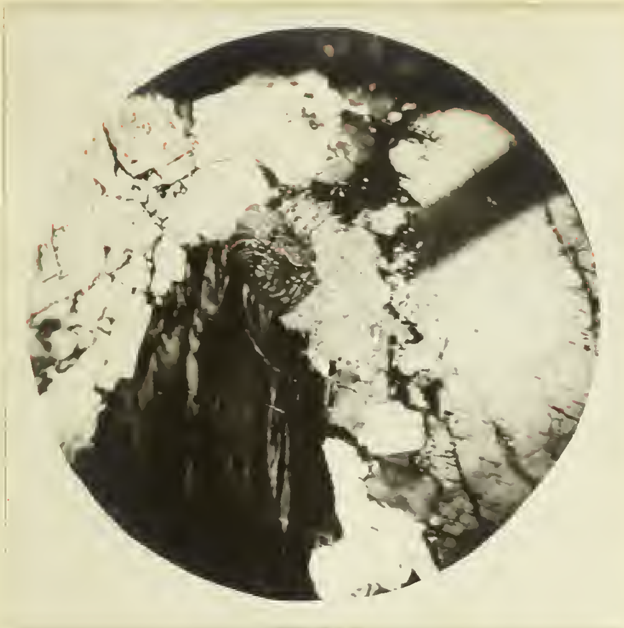
A, Photomicrograph of thin section of the contact between a granite dike(on the left) and its wall rock of gabbro(on the right), showing myrmekite grains(in the center). The myrmekite lies on the contact between labradorite grains(light gray, on the right) and orthoclase(black, on the left). In the center above the myrmekite, are a few quartz grains.

Nicols crossed. x 44.

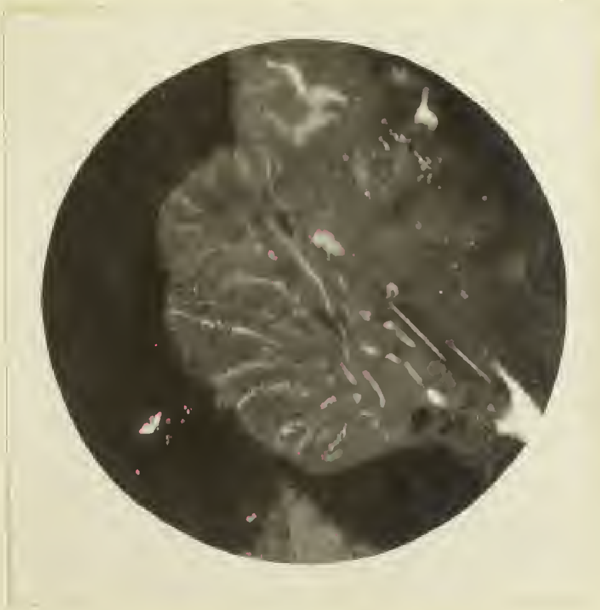
B, Enlarged view of one of the myrmekite grains in the above photograph. The myrmekite(on the right) is convex towards the orthoclase(on the left). The slender, vermicular white areas are quartz, lying in a matrix(dark gray) of albite, or oligoclase.

Nicols crossed. x 207.

Plate XXIII



A.



B.

Plate XXIV.

Plate XXIV.

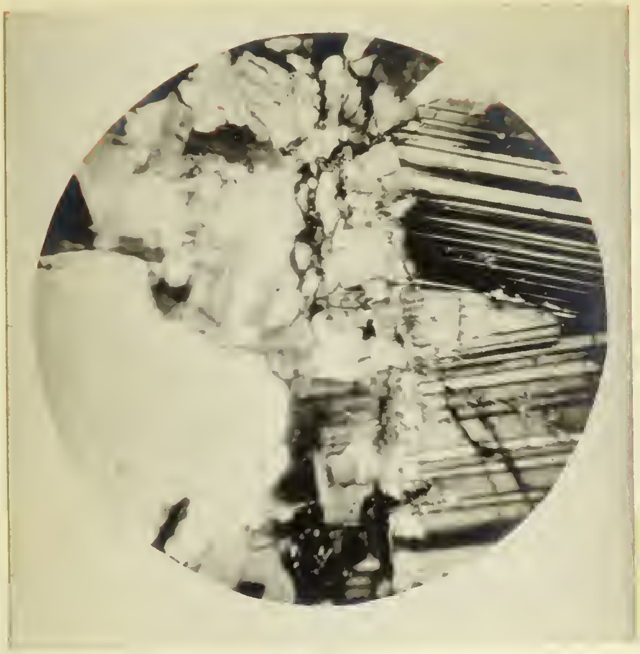
A, Photomicrograph of thin section of the contact between the granite dike and its wall rock of gabbro(on the right), showing a granulated zone along the contact. Myrmekite grains in the central and upper portions of the photograph are fractured, as are also the labradorite grains on the right. The large white area on the left is quartz.

Nicols crossed. x 54.

B, Photomicrograph of thin section of gabbro near the granite dike, showing a large grain of augite with a double rim of green hornblende and green or brown biotite around it. The hornblende does not show up well in the photograph, but it forms a narrow rim around the augite(gray), while blades of biotite((dark-gray or black)penetrate through the hornblende and into the augite parallel to its cleavage. Plagioclase(white or light-gray) is turbid and altered.

Parallel light. x 22.

Plate XXIV



A.

B.

Plate XXV.

Plate XXV.

A, Photomicrograph of thin section of gabbro, showing an enlarged portion of the augite grain shown in Plate XXIV-B. A broad band of biotite surrounds the augite.
Parallel light. x 33.

B, Same, with crossed nicols. This photograph shows how the biotite has penetrated and replaced the plagioclase.

Plate XXV

A

B.

Plate XXVI.

Plate XXVI.

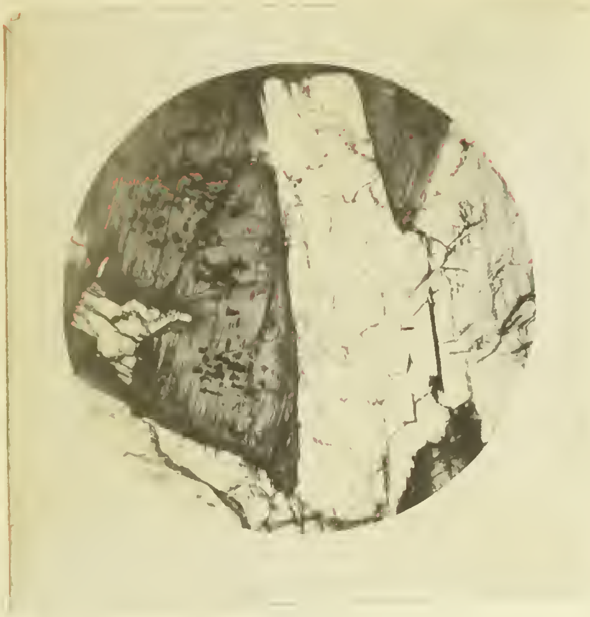
A, Photomicrograph of thin section of gabbro near granite dike, showing plates of rutile(black) which separate in the augite (gray) during its alteration. The narrow, dark-gray rim around the augite is of green hornblende. The white areas are of plagioclase.

Parallel light. x 35.

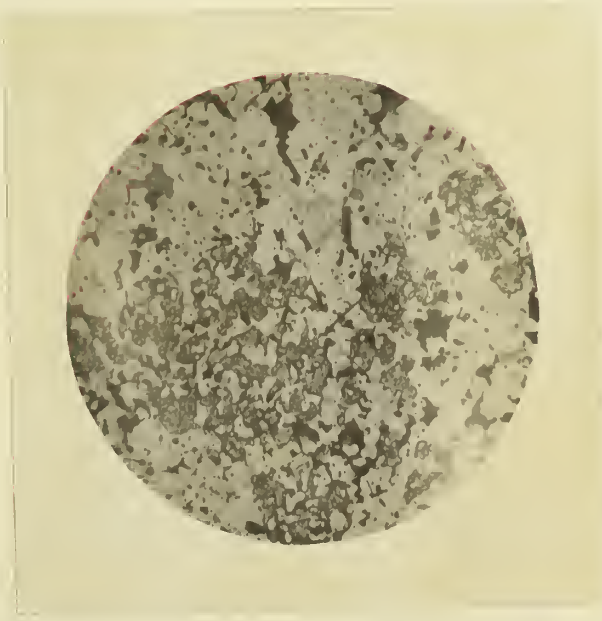
B, Photomicrograph of thin section of contact-metamorphosed slate, showing garnet(dark-gray) enclosing quartz, feldspar, etc.. The white areas are quartz and feldspar; the black area just above the center is blue tourmaline, and the other black areas are brown biotite.

Parallel light. x 24.

Plate XXVI



A



B

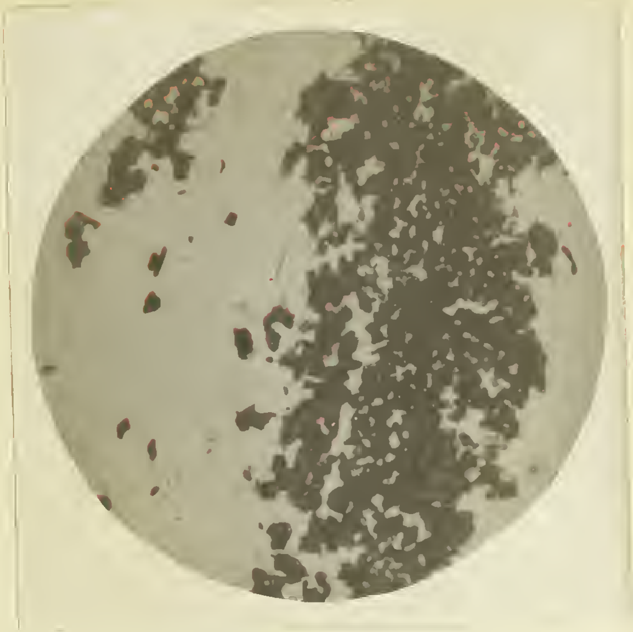
Plate XXVII.

Plate XXVII.

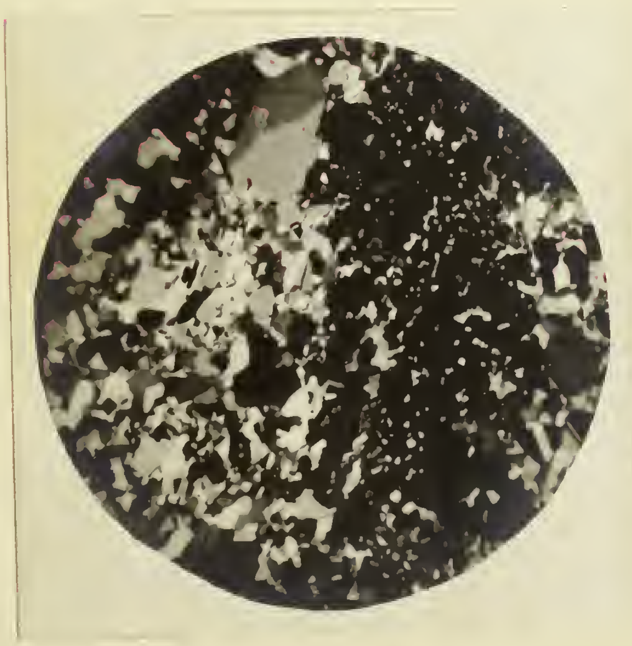
A, Photomicrograph of thin section of cordierite-hypersthene rock from a portion of the Gunflint iron-bearing formation. Light areas are cordierite, and dark areas are hypersthene. Parallel light. x 25.

B, Same, with crossed nicols. Some of the cordierite grains ahow lamellar twinning similar to that of plagioclase.

Plate XXVII



A



B

Plate XXVIII.

Plate XXVIII.

Photomicrograph of thin section of sulphide mass from the contact-metamorphosed quartzite, near the gabbro. The light gray areas are olivine and augite, the white areas are holes in the section, and the black areas are sulphides and magnetite. Parallel light. x 22.

Plate XXVIII

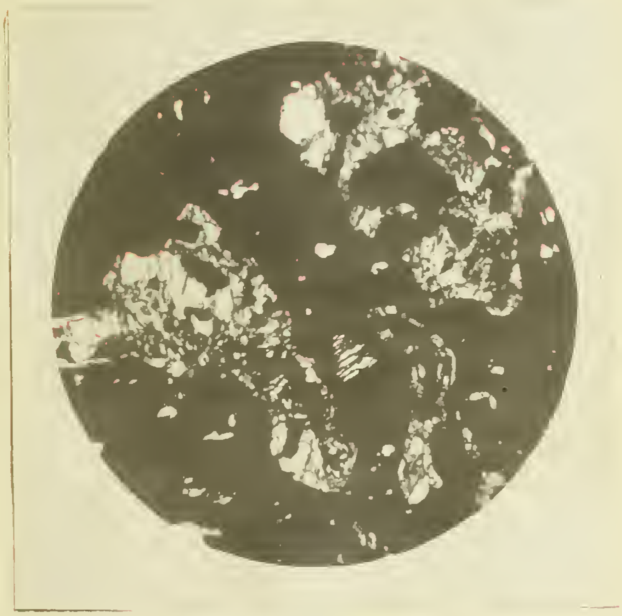


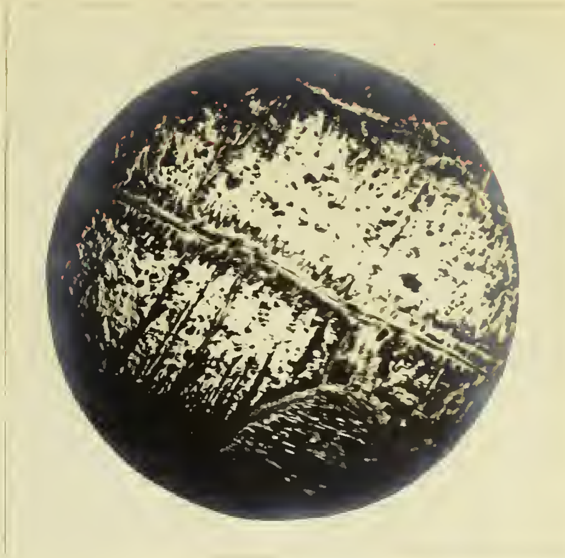
Plate XXIX.

Plate XXIX.

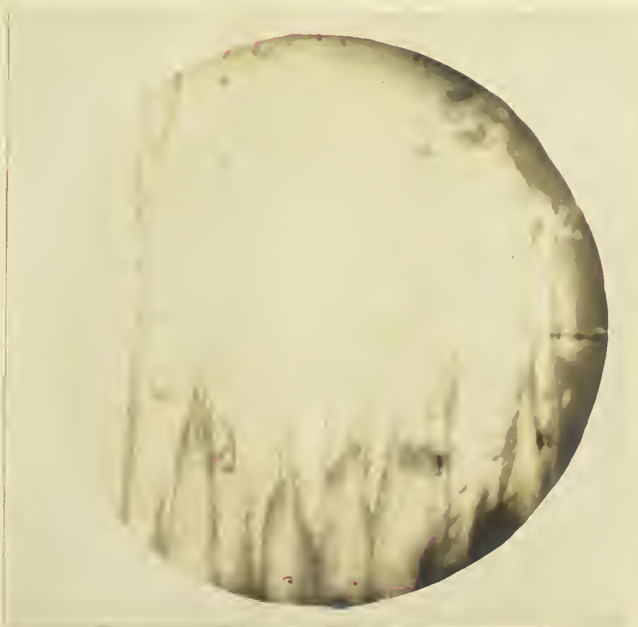
A, Photomicrograph of polished specimen of sulphides from the contact-metamorphosed quartzite near the gabbro, showing the replacement of pyrrhotite(large white, pitted areas) by an unknown grayish-white sulphide. The replacement starts from opposite sides of cracks, and proceeds until the pyrrhotite disappears entirely, or only a small core remains.
Vertical illumination. x 34.

B, An enlarged view of a portion of the area shown in the above photograph, showing how the unknown sulphide(gray) penetrates the pyrrhotite(white) in sharp needles.
Vertical illumination. x 550.

Plate XXIX



A



B

Plate XXX.

Plate XXX.

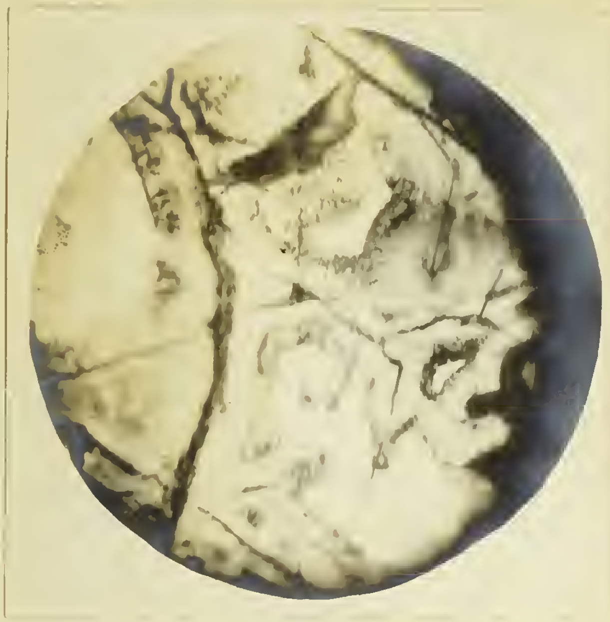
A, Photomicrograph of a polished specimen of sulphides from the Duluth gabbro, showing irregular areas of chalmersite(?) which have been partially replaced by pyrrhotite, the replacement beginning along cracks and proceeding inward on both sides. The faint white areas are chalmersite(?), the roughened, gray areas are pyrrhotite, and the black veinlet on the left is filled with secondary limonite. The black on the right is the edge of the specimen.

Vertical illumination. x 590.

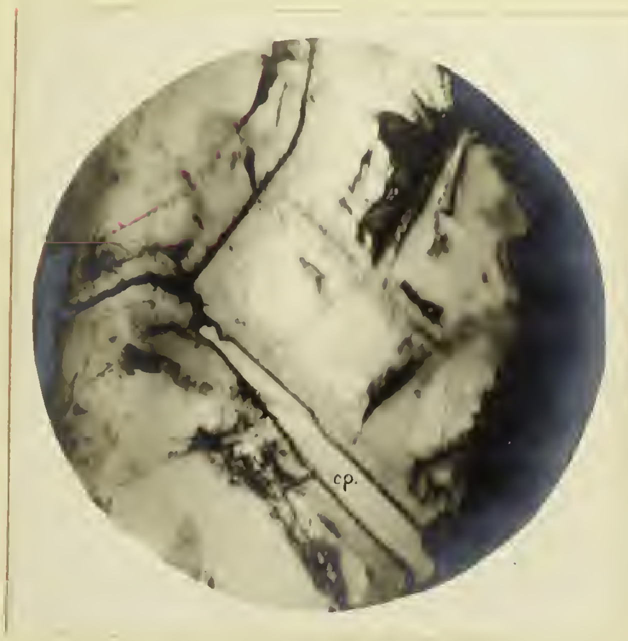
B, Photomicrograph of another portion of the same polished specimen, showing chalmersite(?)(faint white) replaced by pyrrhotite(gray) along cracks. A small tongue of chalcopyrite has penetrated along a crack from the lower right-hand side of the photograph(cp).

Vertical illumination. x 640.

Plate XXX



A



B